

Observing Dark Stars with JWST

Cosmin Ilie^{1*}, Katherine Freese^{1,2}, Monica Valluri³, Ilian T. Iliev⁴, and Paul Shapiro^{2,5}

¹*Michigan Center for Theoretical Physics, Physics Department, University of Michigan, Ann Arbor, MI 48109, USA*

²*Texas Cosmology Center, University of Texas, Austin, TX 78712, USA*

³*Department of Astronomy, University of Michigan, Ann Arbor, MI 49109, USA*

⁴*Department of Physics & Astronomy, University of Sussex, Brighton BN1 9QH, UK*

⁵*Department of Astronomy, University of Texas, Austin, TX 78712, USA*

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ABSTRACT

We study the capability of the James Webb Space Telescope (JWST) to detect Supermassive Dark Stars (SMDS). If the first stars are powered by dark matter heating in triaxial dark matter haloes, they may grow to be very large $> 10^6 M_\odot$ and very bright $> 10^9 L_\odot$. These SMDSs would be visible in deep imaging with JWST and even Hubble Space Telescope (HST). Indeed the object detected at $z \sim 10$ in the recent HST ultra deep field image with the Wide Field Camera 3 (WFC3) may be a SMDS. We use sensitivity limits from previous HST surveys to place bounds on the numbers of SMDSs that may be detected in future JWST imaging surveys. We showed that SMDS in the mass range $10^6 - 10^7 M_\odot$ are bright enough to be detected in all the wavelength bands of the NIRCам on JWST (but not in the less sensitive MIRI camera at higher wavelengths). If SMDSs exist at $z \sim 10, 12$, and 14 , they will be detectable as J-band, H-band, or K-band dropouts, respectively. With a total survey area of 150 arcmin^2 (assuming a multi-year deep parallel survey with JWST), we find that typically the number of $10^6 M_\odot$ SMDSs found as H or K-band dropouts is $\sim 10^5 f_{\text{SMDS}}$, where the fraction of early DM haloes hosting DS is likely to be small, $f_{\text{SMDS}} \ll 1$. If the SMDS survive down to $z=10$ where HST bounds apply, then the observable number of SMDSs as H or K-band dropouts with JWST is $\sim 1 - 30$. While individual SMDS are bright enough to be detected by JWST, standard PopIII stars (without dark matter annihilation) are not, and would only be detected in first galaxies with total stellar masses of $10^6 - 10^8 M_\odot$. Differentiating first galaxies at $z > 10$ from SMDSs would be possible with spectroscopy: the SMDS (which are too cool produce significant nebular emission) will have only absorption lines while the galaxies are likely to produce emission lines as well. Of particular interest would be the HeII emission lines at $\lambda \sim 1.6\mu$ as well as H α lines which would be signatures of early galaxies rather than SMDSs. The detection of SMDSs with JWST would not only provide alternative evidence for WIMPs but would also provide a possible pathway for the formation of massive ($10^4 - 10^6 M_\odot$) seeds for the formation of supermassive black holes that power QSOs at $z = 6$.

Key words: dark matter – first stars – stars: Population III – stars: pre-main-sequence – galaxies: high-redshift

1 INTRODUCTION

The first stars are thought to have formed at $z = 10 - 50$ when the universe was about 200 million years old in $\sim 10^6 M_\odot$ (mini) halos consisting of 85% DM and 15% baryons in the form of H and He from big bang nucleosynthesis. Their formation marks the end of the “dark ages” of the Uni-

verse. For reviews of the standard picture of the formation of the first stars see Barkana & Loeb (2001); Yoshida et al. (2003); Bromm & Larson (2004); Ripamonti & Abel (2005); Bromm et al. (2009).

Spolyar et al. (2008) first showed that dark matter heating may drastically alter the picture of formation for these first stars. The canonical example of particle DM is Weakly Interacting Massive Particles (WIMPs). In many theories WIMPs are their own antiparticles and annihilate

* E-mail: cilie@umich.edu

with themselves wherever the DM density is high. In fact, this annihilation process is exactly what is responsible in the early Universe for leaving behind the correct relic WIMP abundance today to solve the dark matter problem, 24% of the energy density of the universe. The same annihilation process would then take place also in the collapsing proto-stellar clouds at the centers of minihalos. At suitably high baryonic density in these clouds, the annihilation products get stuck inside the cloud and prevent it from undergoing further collapse. The annihilation products thermalize with the baryons and provide a very powerful heat source. Indeed, the object becomes a "dark star", which, despite its name, shines very bright. The DM – while only a negligible fraction of the star's mass – provides the key power source for the star through DM heating. Note that the term 'Dark' refers to the power source, not the content of the star. These first Dark Stars are stars made primarily of hydrogen and helium with a smattering of dark matter ($<1\%$ of the mass consists of DM); yet they shine due to DM heating.

Recently there has been much excitement in the dark matter community about hints of WIMP detections in a number of experiments: excess positrons in the PAMELA satellite (Adriani et al. 2009; Abdo et al. 2010; Adriani et al. 2010) may be due to DM annihilation (though alternative astrophysical explanations are more likely). Excess γ -rays in the FERMI satellite (Abdo et al. 2009b,a; Dobler et al. 2010; The Fermi LAT Collaboration 2011) may be due to DM annihilation; and annual modulation (Drukier et al. 1986; Freese et al. 1988) in direct detection experiments DAMA (Bernabei et al. 2010) and COGENT (Aalseth et al. 2011). The CRESST experiment (Angloher et al. 2011) also has unexplained events.

The WIMP annihilation rate is $n_\chi^2 \langle \sigma v \rangle$ where n_χ is WIMP density and we take the standard annihilation cross section

$$\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3/\text{s}, \quad (1)$$

and WIMP masses in the range 1 GeV-10 TeV. WIMP annihilation produces energy at a rate per unit volume

$$\hat{Q}_{DM} = n_\chi^2 \langle \sigma v \rangle m_\chi = \langle \sigma v \rangle \rho_\chi^2 / m_\chi, \quad (2)$$

where n_χ is the WIMP number density, m_χ is the WIMP mass, and ρ_χ is the WIMP energy density. The annihilation products typically are electrons, photons, and neutrinos. The neutrinos escape the star, while the other annihilation products are trapped in the dark star, thermalize with the star, and heat it up. The luminosity from the DM heating is

$$L_{DM} \sim f_Q \int \hat{Q}_{DM} dV \quad (3)$$

where f_Q is the fraction of the annihilation energy deposited in the star (not lost to neutrinos) and dV is the volume element. We take $f_Q = 2/3$ as is typical for WIMPs.

Dark stars are born with masses $\sim 1M_\odot$. They are giant puffy (~ 10 AU), cool (surface temperatures $< 10,000\text{K}$), yet bright objects (Freese et al. 2008a). They reside in a large reservoir ($\sim 10^5 M_\odot$) of baryons, i.e., $\sim 15\%$ of the total halo mass. These baryons can start to accrete onto the dark stars. Dark stars can continue to grow in mass as long as there is a supply of DM fuel. We consider two different mechanisms that can continually provide the req-

uisite dark matter fuel, allowing them to become supermassive dark stars (SMDS) of mass $M_{DS} > 10^5 M_\odot$.

1) **Extended Adiabatic Contraction (AC):** the central dark matter density is enhanced due to an increase in the depth of the gravitation potential well due to the infall of baryons. We treat this gravitational effect via the Blumenthal method for adiabatic contraction. While this approach is simple to implement, we Freese et al. (2009) and others Natarajan et al. (2009); Iocco et al. (2008) have previously shown that it provides dark matter densities accurate to within a factor of two, which is perfectly adequate for these studies. In the central cusps of triaxial DM halos DM particles follow a variety of centrophilic orbits (box orbits and chaotic orbits Valluri et al. 2010) whose population is continuously replenished, allowing DM annihilation to continue much longer than in spherical DM halos. The period of extended AC can thus last for a very long time (hundreds of millions of years or more). Freese et al. (2010a) showed that this replenishment of the DM in the central cusp could be used to followed the growth of dark stars from their inception at $1M_\odot$, till they become supermassive dark stars (SMDS) of mass $M_{DS} > 10^5 M_\odot$.

2) **Capture:** As a second mechanism for dark matter refueling, we take the star to be initially powered by the DM from adiabatic contraction (AC), but assume the AC phase is short $\sim 300,000$ years; once this DM runs out, the star shrinks, its density increases, and subsequently the DM is replenished inside the star by capture of DM from the surroundings (Freese et al. 2008b; Iocco 2008; Sivertsson & Gondolo 2011) as it scatters elastically off of nuclei in the star. In this case, the additional particle physics ingredient of WIMP scattering is required. This elastic scattering is the same mechanism that direct detection experiments (e.g. CDMS, XENON, LUX, DAMA, COGENT, COUPP, CRESST) are using in their hunt for WIMPs.

Supermassive dark stars can result from either of these mechanisms for DM refueling inside the star. Umeda et al. (2009) considered a different scenario which also results in SMDSs. In all of these cases SMDSs can live for a very long time, tens to hundreds of million years, or possibly longer (even to today). We find that SMDS of mass $M_{DS} > 10^6 M_\odot$ SDMSs are very bright $> 3 \times 10^9 L_\odot$ which makes them potentially observable by the James Webb Space Telescope (JWST).

The key ingredient that allows dark stars to grow so much larger than ordinary fusion powered Population III stars is the fact that dark stars are so much cooler. Ordinary Pop III stars have much larger surface temperatures in excess of 50,000K. They produce ionizing photons that provide a variety of feedback mechanisms that cut off further accretion. McKee & Tan (2008) have estimated that the resultant Pop III stellar masses are $\sim 140M_\odot$. The issue of the initial mass function for Pop III stars is far from being solved. Recent simulations (see Clark et al. 2011; Greif et al. 2011a,b) indicate that the typical mass of such objects is much lower than previously thought. Dark stars are very different from fusion-powered stars, and their cooler surface temperatures allow continued accretion of baryons all the way up to enormous stellar masses, $M_{DS} > 10^5 M_\odot$.

In this paper we discuss detectability of these objects in the upcoming JWST. In future work we will investigate how well other observations with Herschel, SPITZER, GMT,

TMT and other instruments can detect or place bounds on Dark Stars. We restrict our discussion only to SMDS of mass $10^6, 10^7 M_\odot$ (we show that SMDS of 10^5 and lower are hard to detect). Previously Zackrisson et al. (2010a) studied dark stars of even lower masses, and concluded that even $\lesssim 10^3 M_\odot$ DS could be detected as individual objects with JWST if their fluxes were magnified by gravitational lensing by a well-placed foreground cluster. Since supermassive dark stars are larger and brighter, they are easier to detect. A preliminary study of detectability with JWST and HST of supermassive Dark Stars was made in Freese et al. (2010a) and Freese et al. (2010b). Freese et al. approximated the spectrum of the SD as a pure blackbody determined by its temperature and radius and used it to show that individual SMDS would be detectable with JWST and HST. In this paper we improve our estimate by using spectra from the TLUSTY model stellar atmospheres code for zero-metallicity atmospheres from the work of Zackrisson et al. (2010b).

SMDS formed via Extended AC are easier to detect than those formed with capture. Those formed "with capture" are somewhat hotter (by a factor of few) and have radii smaller by a factor of 5-10 for the same stellar mass. Because they are hotter, their peak wavelength moves out of the most sensitive ranges for HST and JWST, and their fluxes in the detectors are lower.

Once the SMDS run out of DM fuel, they contract and heat up till the core reaches $10^8 K$ and fusion begins. Due to their extremely large masses the fusion-powered phase is short and the SMDSs collapse to form massive black holes of mass $10^4 - 10^6 M_\odot$. Again, this prediction is different from standard Pop III stars, many of which explode as pair-instability supernovae (Heger & Woosley 2002) with predicted even/odd element abundance ratios that are not (yet) observed in nature. These massive black holes remnants could provide the moderately massive "seeds" for the formation of nuclear supermassive black holes accounting for the existence of $10^9 M_\odot$ BHs (Haiman & Loeb 2001) which are the central engines of the most distant ($z \gtrsim 6$) quasars in the Sloan Digital Sky Survey (SDSS) (Fan et al. 2001, 2004, 2006). Indeed direct collapse of very metal-poor, low-angular momentum gas via dynamical instabilities (Loeb & Rasio 1994; Begelman et al. 2006; Lodato & Natarajan 2006) has been proposed as a way to form massive "seed" black holes of $10^4 - 10^6 M_\odot$ at redshifts of 10-15. These massive seed formation scenarios however, are difficult to confirm observationally since the BHs form in compact, low luminosity cold gas disks and the BH formation is accompanied by a sudden burst of with a luminosity of $10^9 L_\odot$. In contrast if the "seeds" form from SMDSs, they may well shine for $10^6 - 10^7$ years prior to their collapse to a BH, enabling them to be detected by JWST.

SMDS could also make plausible precursors of Intermediate Mass Black Holes; and account for the BHs inferred by extragalactic radio excess seen by the ARCADE experiment (Seiffert et al. 2009). In addition, the BH remnants from DS could play a role in high-redshift gamma ray bursts thought to take place due to accretion onto early black holes (Narayan et al. 2001)

The possibility that DM annihilation might have effects on *today's* stars was initially considered in the '80s and early '90s (Krauss et al. 1985; Press & Spergel 1985;

Bouquet & Salati 1989; Salati & Silk 1989) and has recently been studied in interesting papers by Moskalenko & Wai (2007); Scott et al. (2007); Bertone & Fairbairn (2008); Scott et al. (2008); Casanellas & Lopes (2009); Hooper et al. (2010); Scott (2010).

Several authors have explored the repercussions of DM heating in the first stars including: Spolyar et al. (2008); Freese et al. (2008b,a); Spolyar et al. (2009); Taoso et al. (2008); Yoon et al. (2008); Iocco et al. (2008); Ripamonti et al. (2009); Schleicher et al. (2009); Gondolo et al. (2010); Ripamonti et al. (2010); Sivertsson & Gondolo (2011); Casanellas & Lopes (2011); Hirano et al. (2011); Iocco (2010); Ilie et al. (2011); Scott (2010).

The effects of DS (and those of the resultant main sequence stars) on reionization was studied by Schleicher et al. (2008, 2009) and more recently by Scott et al. (2011) as discussed below.

In this paper we follow the approach taken by Zackrisson et al. (2010b, 2011b). Similar to their work, we use SMDS spectra from the TLUSTY code; compute the formation rate of DSs by counting DM haloes in N-body simulations; and use HST data to bound the numbers of SMDS that survive to $z=10$ and therefore the numbers that may be seen with JWST. Their study focused on $10^7 M_\odot$ SMDS while we consider lower mass ones as well. We go beyond their work by studying SMDS as H and K-band dropouts with JWST, where JWST can really improve upon all previous data sets.

The paper is organized as follows. In Section II we describe the spectra of SMDS obtained by using the TLUSTY code. In Section III we compute formation rate of DSs, by counting DM halos in a N-body simulation of structure formation at $z > 10$ carried out with the Cube P³M code (Iliev et al. 2010) and assuming that some fraction f_{SMDS} of these early halos will host DS. In Section IV, we examine the detectability of SMDS in Hubble Space Telescope (HST). In fact HST has seen objects out to $z \sim 10$, and it is interesting to speculate that HST could already have seen SMDS if they survive to redshift $z=10$. With current imaging data it is impossible to differentiate between an early galaxy composed of PopIII stars from a SMDS. However, the fact that HST has only seen one object at this high redshift can be used to set bounds (Zackrisson et al. 2010a) the numbers of dark stars at $z \sim 10$. In Section V we show that dark stars may be detected in a variety of JWST filters, and in particular may show up as J-band, H-band, or K-band dropouts; such a detection would then gives an indication of their redshift. In Section VI, we compare early galaxies at high redshifts (consisting of PopIII stars with different IMFs) with SMDS, which will look very similar with JWST, and start a discussion of ways to differentiate between them. In Section VII we conclude and summarize the results of our study.

2 DARK STAR SPECTRA

In this section we present spectra of SMDS obtained with the publicly available TLUSTY (Hubeny 1988) synthetic stellar atmospheres code. As discussed in Freese et al. (2010a), SMDS formed via captured DM are much hotter than SMDS formed via extended AC. Also, stars formed via capture

undergo a Kelvin-Helmholz contraction phase prior to DM capture, hence their radii are 5-10 times smaller than those SMDS of the same mass formed via the extended AC mechanism. Since Dark Stars are composed of primordial hydrogen and helium, no other elements are assumed to be present in the atmosphere and, hence all the observed spectral lines are those of H and He. However the differences in the temperature and radii of SMDS formed via these two mechanisms are responsible for the differences in the spectra in the two panels of Figure 1. The left panel shows the spectrum for a $10^6 M_\odot$ dark star with surface temperature $T_{eff} = 1.9 \times 10^4 K$ which grew via extended AC. The Lyman edge is seen at roughly 0.1 microns¹. Similarly, Figure 1 (right) illustrates the spectrum for a $10^6 M_\odot$ and $T_{eff} = 5.1 \times 10^4 K$ DS which grew via captured DM. The most prominent differences from the left panel are a shift of the peak in the spectrum to lower wavelengths and a steeper UV continuum slope β ($f_\lambda \propto \lambda^\beta$). Despite the fact that the SMDS formed via capture is hotter, its significantly smaller radius makes it harder to detect in the near infrared at redshifts of ~ 10 and above.

There are significant differences in the spectra the two cases. In the left panel (extended AC), the lower surface temperature ($\sim 2 \times 10^4 K$) implies a significant fraction of neutral H and He remain in the stellar atmosphere resulting in strong absorption lines at wavelengths corresponding to the Lyman series (0.1216 μm -0.0912 μm). At shorter wavelengths we notice another break in the spectrum due to neutral helium (HeI) absorption ($\sim 0.05 \mu m$ -0.06 μm). In the right panel (“with capture”), the higher surface temperature ($T_{eff} \sim 5 \times 10^4 K$) implies that H is ionized hence the Lyman absorption lines are weaker. The break in the spectrum in Figure 1 right panel corresponds to absorption by singly ionized helium (HeII) at wavelengths ranging between 0.023 μm and 0.030 μm . In the left panel HeI lines appear at wavelengths $\sim [0.3 \mu m$ -0.45 $\mu m]$, HeII lines at wavelengths $\sim 0.46 \mu m$, and more HeI lines at $\sim [0.47 \mu m$ -0.7 $\mu m]$. The same lines, with somewhat weaker strength, are seen in the right panel. In both cases we note a sequence of absorption lines between $\sim [0.8 \mu m$ -1.0 $\mu m]$, which correspond to HeI absorption.

3 DARK STAR FORMATION RATE

The first Dark Stars can form in the early Universe inside minihalos of $\sim 10^6 M_\odot$, where protostellar clouds collapse via molecular hydrogen cooling until the DM heating sets in. Later in $10^8 M_\odot$ halos, where clouds collapse via atomic line radiative cooling, larger DS can form. To compute the detection rate of SMDS with JWST we need to know the formation rate of $10^6 - 10^8 M_\odot$ dark matter halos. If we assume that a fraction f_{SMDS} of these halos contain Dark Stars we can use this to compute the formation rate of DSs. We

¹ Compared to a blackbody of the same temperature, photons below the Lyman edge have typically been shifted to higher wavelengths (lower energy) by absorption and rescattering. However, the excess seen at wavelengths just below the Lyman edge is due to photons coming from deeper inside the star (the photosphere is at roughly an optical depth ~ 1 , and at this wavelength there is very little absorption).

will attempt to set constraints on this fraction by using the fact that a single $z = 10$ object was observed in recent HST ultra deep field observations with the Wide Field Camera 3 (Bouwens et al. 2011, hereafter HUDF09).

A similar study by Zackrisson et al. (2010b, 2011b) for the case of $10^7 M_\odot$ SMDS concluded that the prior null detection of $z = 10$ objects in first year HUDF09 observation (Bouwens et al. 2010), was sufficient to rule out the detection of $10^7 M_\odot$ SMDS with JWST. However these authors did not consider the effect of the time it takes the SMDS to grow when computing the formation rates for DM halos that could host such objects. This effect is transparent in Table 1 in the differences between what we labeled as z_{start} (the redshift that should be used when computing the formation rate of DM halos) and z_{form} (the redshift when the DS reaches its final mass). Consideration of a finite time required for the SMDS to grow (following the formation of its host DM halo) significantly lowers the bounds predicted from HST, since to be visible at $z = 10$ the more massive DM halos has to have formed at a higher redshifts, where they are rarer. In addition we consider the case of the $10^6 M_\odot$ SMDS, since these objects are likely to be more numerous, are detectable with JWST, and are also subject to bounds from existing HST observations.

We use N-Body simulations of structure formation at high redshifts from Iliev et al. (2010) carried out with the CubeP³M N-Body code, developed from the particle-mesh PM-FAST (Merz et al. 2005). This high resolution simulation considers a comoving volume of $6.3 h^{-1} \text{ Mpc}$ with 1728^3 particles of mass $5.19 \times 10^3 M_\odot$, hence is able to resolve halos of mass $\gtrsim 5 \times 10^5 M_\odot$. We compute the formation rate (dn/dt as a function of redshift per comoving Mpc^3 per year), of minihalos with masses within different mass ranges. Figure 2 shows the formation rate of halos in two mass ranges that spans a factor of two in mass ($10^7 - 2 \times 10^7 M_\odot$ and $10^8 - 2 \times 10^8 M_\odot$) while Figure 3 shows the formation rate of halos in two mass ranges that span a factor of five in mass ($10^7 - 5 \times 10^7 M_\odot$ and $10^8 - 5 \times 10^8 M_\odot$).

We computed the formation rate of DM minihalos using two different sets of bin widths, to show that the results are relatively insensitive to this issue. As our canonical case, we computed the formation rate dn/dt of minihalos per $\text{Mpc}^{-3} \text{yr}^{-1}$ formed in a bin whose width is a factor of two in mass (Figure 2). dn/dt as a function of redshift is shown for halos in the mass range $(1-2) \times 10^7 M_\odot$ (left panel) and for halos in the mass range $(1-2) \times 10^8 M_\odot$ (right panel). We assume that since the baryonic fraction initially in the halo is roughly 15%, we assume that a DS forming in a halo of a given mass can attain at most 10-15% of the mass of its host halo. Following Freese et al. 10 we assume that the DS can grow with an accretion rate of $\sim 1 M_\odot$ to the point where it consumes a significant fraction of the baryons in the halo. In other words, we assume that a $10^7 M_\odot$ SMDS will form in a $(1-2) \times 10^8 M_\odot$ minihalo. While this is an unlikely scenario, which involves most of the baryons in the halo being accreted into a single central object, we will see that even with this assumption, detection rates of SMDS with JWST are fairly small. The formation rates in Scenario I are plotted in Figure 2.

As a check, we also broadened the range of DM halo masses in which DS form by allowing halo masses to span a factor of five in mass. Figure 3 (left panel) shows the

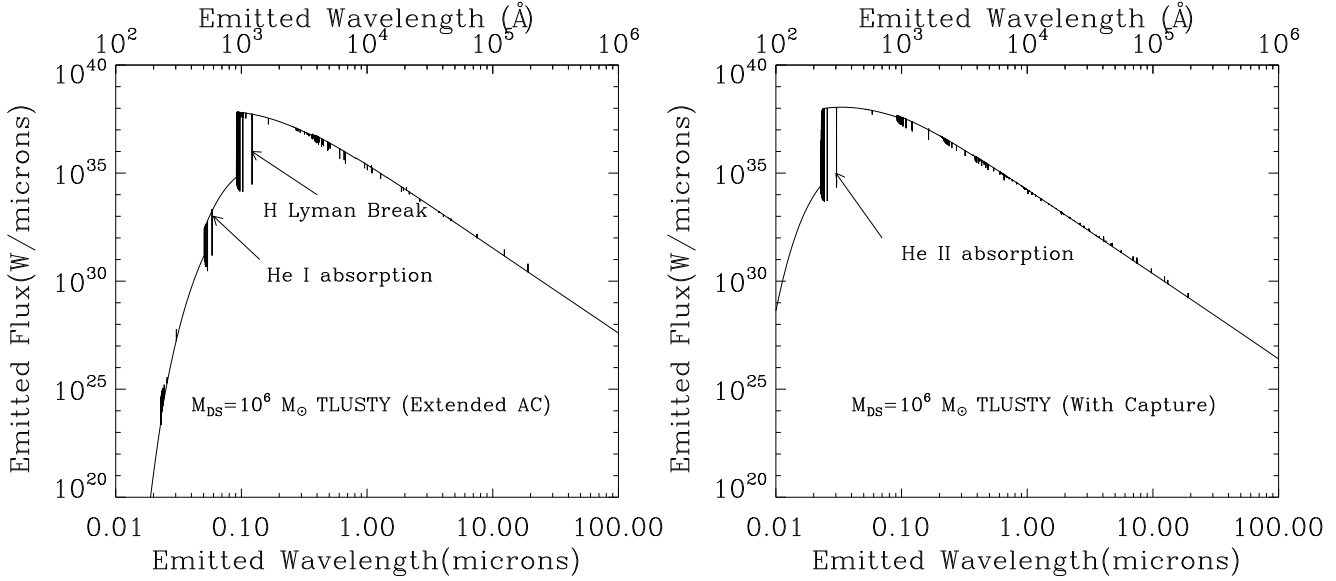


Figure 1. Expected spectral energy distribution (SEDs) of $10^6 M_\odot$ supermassive dark stars. Left panel: DS with a surface temperature of $1.9 \times 10^4 \text{K}$ and formed via the extended adiabatic contraction (AC) only mechanism. Right panel: with a surface temperature of 5.1×10^4 and formed “with capture”.

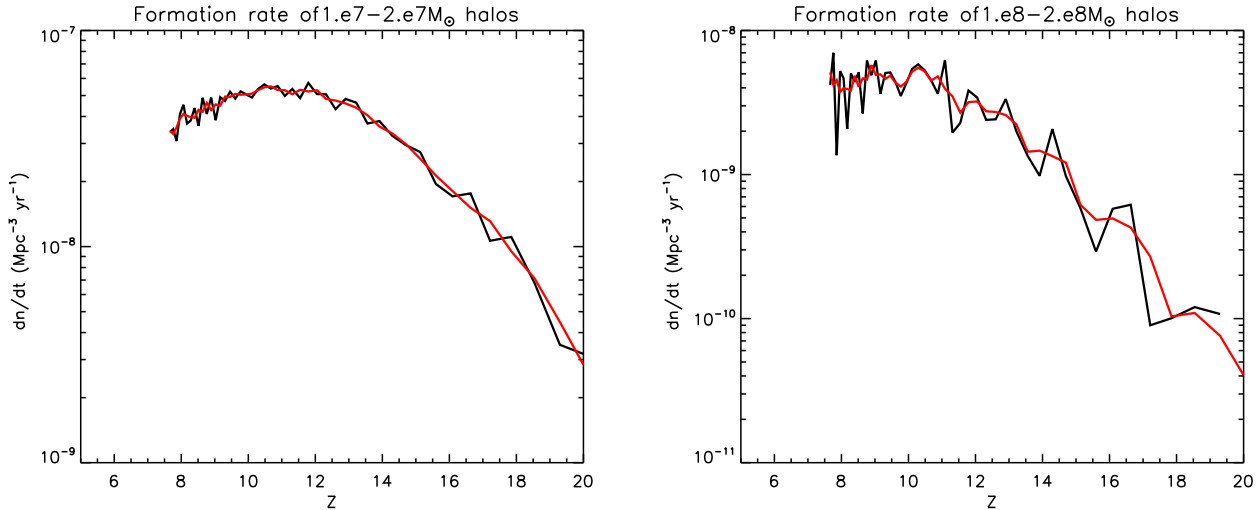


Figure 2. Left: the formation rate of $1 - 2 \times 10^7 M_\odot$ minihalos per comoving Mpc^3 and year. These halos are potential hosts for the $10^6 M_\odot$ SMDS. Right: formation rate for $1 - 2 \times 10^8 M_\odot$ minihalos in which a $10^7 M_\odot$ SMDS can form. The black lines correspond to the formation rate computed directly from the N-body simulation and the smoother red lines (obtained by computing a running average) simply improve visibility of the general trend.

formation rate dn/dt as a function of redshift for halos in the mass range $(1-5) \times 10^7 M_\odot$ and the right panel indicates the formation rate of halos in the mass range $(1-5) \times 10^8 M_\odot$. In this scenario the SMDS is 10–50 times smaller than its host halo, and is more realistic since in this case all the baryons in the halo are not accreted by the DS.

A comparison of Figures 2 and 3 shows that the formation rate of host halos does not vary significantly between the two scenarios (at most by a factor of 3). Henceforth, in the remainder of this study, we will always take the halo mass range to span a factor of two in mass.

We define z_{start} to be the (approximate) formation redshift of minihalos capable of hosting DS, allowing for an

uncertainty of a unit redshift interval; i.e. the minimum redshift of minihalo formation is $z_{\text{min}} = z_{\text{start}} - 1/2$ while the maximum redshift is $z_{\text{max}} = z_{\text{start}} + 1/2$. We make a distinction between z_{start} the redshift of formation of the DM halo capable of hosting a DS (initial $\sim 1 M_\odot$ mini dark stars come into existence very soon after this redshift), and z_{form} the redshift of formation of the SMDS. Between z_{start} and z_{form} the DS grows by accreting baryons at a rate of $10^{-2} - 10^{-1} M_\odot/\text{yr}$ growing over this period to a supermassive size of $\sim 10^5 - 10^7 M_\odot$. This difference between z_{start} and z_{form} is crucial to accounting for the differences between the results presented in this paper and previous

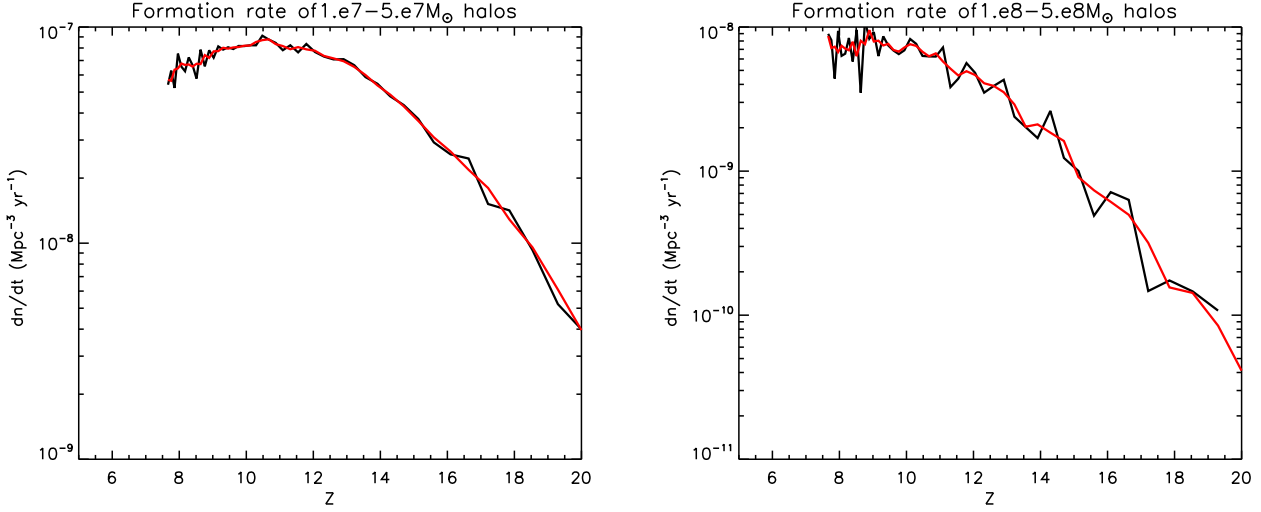


Figure 3. As in Figure 2, but with the larger mass bin width (see scenario II in text). In the left panel we plot the formation rate of minihalos with a mass in the $1 - 5 \times 10^7 M_\odot$ range, where a DS of $10^6 M_\odot$ could form. The panel on the right is for halos in the $1 - 5 \times 10^8 M_\odot$ range, where a DS of $10^7 M_\odot$ could form.

work (Zackrisson et al. 2010b) where this additional time required to grow supermassive was not allowed for.

The formation rate of minihalos per unit redshift and arcmin² is then given by

$$\frac{dN}{dzd\theta^2} = \frac{dn}{dt} (V_c(z_{\min}) - V_c(z_{\max})) \frac{C}{4\pi} \Delta t(\min; \max), \quad (4)$$

where, V_c denotes the comoving volume at a given redshift, C is the conversion factor between arcmin² and steradians, and $\Delta t(\min; \max)$ is the cosmic time interval between z_{\min} and z_{\max} :

$$\Delta t(\min; \max) = t_H \int_{z_{\min}}^{z_{\max}} \frac{1}{(1+z)(\Omega_m(1+z)^3 + \Omega_\Lambda)^{\frac{1}{2}}}. \quad (5)$$

The N-body simulations from which the halo formation rates are computed as well as other calculations assume a standard Λ CDM Universe in which $\Omega_m = 0.27$ is the cosmic matter density and $\Omega_\Lambda = 0.73$ is the cosmic dark energy density or cosmological constant with parameters from WMAP5 data Komatsu et al. (2009).

We consider three possible redshifts z_{form} by which the DS has accreted enough baryons to become supermassive:

- Case A: $z_{\text{form}} = 10$
- Case B: $z_{\text{form}} = 12$
- Case C: $z_{\text{form}} = 15$

In principle the accretion rate and the final mass of the SMDS in these three cases will imply three different values of z_{start} at which the relevant minihalos formed. To simplify the situation we assume a fixed accretion rate of $10^{-1} M_\odot / \text{yr}$ to determine the values for z_{start} (Table 1 column 5) and using corresponding dn/dt values from Figure 2 (Table 1 column 6) at $z = z_{\text{start}}$, we evaluate $\frac{dN}{dzd\theta^2}$ using Equation(4) (Table 1, column 7). These values of $\frac{dN}{dzd\theta^2}$ will be used in sections to follow.

4 SUPERMASSIVE DARK STARS WITH HUBBLE SPACE TELESCOPE

In this section we examine the observability of dark stars with existing Hubble Space Telescope (HST) surveys, speculating that HST may already have seen such objects, if they survive to redshift $z = 10$. We will adopt the standard "dropout technique" pioneered by Steidel et al. (1996) and applied recently to J and H band observations of the Hubble Ultra Deep Field (HUDF09) by (Bouwens et al. 2011; Oesch et al. 2011) to detect a candidate galaxy at $z = 10$ as a "J-band dropout." This photometric redshift determination method requires a 5-sigma detection of an object in one band but a non-detection in an adjacent band of lower wavelength. In the case of the "J-band drop out" observed with HST, the object was observed in the 1.60μ (H-band) but was *not* seen in the 1.15μ (Y-band) or 1.25μ (J-band). The absence of emission in the latter bands is assumed to occur due to Ly- α absorption by hydrogen clouds in between the source and us, allowing for an approximate estimate of the redshift of the object. More specifically we take as our dropout criterion

$$\Delta m_{AB} \geq 1.2 \quad (6)$$

where Δm_{AB} is the difference in apparent magnitude between the two bands of observation, in this case the J and H bands. Observations at longer (near to mid IR) wavelengths are required for photometric determination of objects more distant than $z = 10$, necessitating JWST observations. Bouwens et al. (2011) and Oesch et al. (2011) find a candidate $z \sim 10$ object in the co-added first and second year observation of the HUDF with the new WFC3/IR camera as a J-band dropout. This object is currently thought to be a galaxy, the most distant one observed to date, since the SED is a reasonable match to that of galaxies at $z > 9$ and it appears clearly extended (Oesch et al. 2011). However the absence of spectra and the poor spatial resolution

Scenario Name	Halo Mass Range (M_\odot)	M_{DS} (M_\odot)	z_{form}	z_{start}	dn/dt ($\text{Mpc}^{-3}\text{yr}^{-1}$)	$\frac{dN}{dzd\theta^2}$ arcmin $^{-2}$
A	$(1-2) \times 10^8$	10^7	10	13	5×10^{-9}	235
B	$(1-2) \times 10^8$	10^7	12	16	7×10^{-10}	16
C	$(1-2) \times 10^8$	10^7	15	22	1×10^{-10}	0.77
A	$(1-2) \times 10^7$	10^6	10	10.7	5×10^{-8}	4435
B	$(1-2) \times 10^7$	10^6	12	12.8	6×10^{-8}	2965
C	$(1-2) \times 10^7$	10^6	15	16	2×10^{-8}	466

Table 1. DM halo formation rates: dn/dt expressed in $\text{Mpc}^{-3}\text{yr}^{-1}$, and $\frac{dN}{dzd\theta^2}$ as number formed per unit redshift and arcmin 2 for cases considered in the text. Top three rows A-C are for a $10^7 M_\odot$ SMDS forming DM halos of mass $(1-2) \times 10^8 M_\odot$; bottom three rows are for the $10^6 M_\odot$ SMDS forming in DM halos of mass $(1-2) \times 10^7 M_\odot$. We have assumed that the DS started accreting baryons with a constant rate of $10^{-1} M_\odot/\text{yr}$ at z_{start} and reached its final mass by z_{form} .

of the image allow us to consider the possibility that this object could instead be a SMDS. Even though it may be hard to identify a DS uniquely with HST, the fact that at most one candidate has been found can be used to place bounds on the numbers of dark stars at redshifts up to $z = 10$. In this section we examine the observability of DS of various masses in existing HST imaging surveys, and in a later section examine the resulting bounds for future surveys with JWST.

4.1 Comparison of DS stellar output with HST Sensitivity

Figures 4-6 plot the predicted apparent magnitudes of Dark Stars of $10^4 - 10^7 M_\odot$ at various redshifts and compare these predictions to sensitivity of various HST surveys (plotted as thin horizontal lines) in two HST filters WFC3 F125 (J-band, colored blue) and F160 (H-band, colored red). In these figures, we have assumed that the SMDS formed at $z=15$ and survived to various redshifts as shown. In figures 4 and 5, the Dark Stars are considered to be formed via the extended adiabatic contraction mechanism, without any captured DM; while in Figure 6, we consider the case with capture.

The thick solid curves show the apparent magnitudes M_{AB} for Dark Stars of various masses as a function of redshift in the J_{125} (F125W, blue) and H_{160} (F160W, red). These solid curves are generated using simulated atmospheres spectra from TLUSTY (Fig 1) and redshifting them, $(F_\nu(\lambda; z))$, imposing a cutoff at wavelengths lower than the Lyman- α if $z \gtrsim 6$, assuming that photons at those wavelengths will be absorbed by the neutral hydrogen in the IGM. We use the H and J passbands throughput curves $(T^{H,J}(\lambda))$ for the HST WFC3, found at <http://www.stsci.edu/~WFC3/UVIS/SystemThroughput/>, to compute the observed apparent magnitudes:

$$m_{AB}^{J,H} = -2.5 \log \left(\frac{\int d\lambda \lambda T^{H,J}(\lambda) F_\nu(\lambda; z)}{\int d\lambda \lambda T^{H,J}(\lambda)} \right) + 31.4 \quad (7)$$

The constant 31.4 is necessary to convert the fluxes to units of nJy. $F(\lambda; z)$ is defined by:

$$F_\nu(\lambda; z) = \frac{(1+z)L_{\nu'}(\lambda')}{4\pi D_L^2(z)}, \quad (8)$$

where λ is the redshifted wavelength, i.e. $\lambda = (1+z)\lambda'$ and $L_{\nu'}(\lambda')$ is the emitted flux (we use TLUSTY to estimate it). The luminosity distance is labeled by $D_L(z)$ and depends

on the chosen cosmology. We define a J-band dropout to be any observation to the right of the green vertical line, corresponding to a difference in apparent magnitudes of 1.2 or larger between the J and H filters as defined in Eq.(6), (the same criterion as used by Oesch et al. (2011)). The location of the green line shows that J-band drop out technique will also identify the redshift of any SMDS found in this way to be at $z \sim 10$.

In Figure 4 the sensitivity limits from various deep field surveys compiled by Oesch et al. (2011): HUDF09, HUDF09-1, HUDF09-2, Early Release Science Data (ERS), CANDELS-Deep and CANDELS-Wide are indicated by different line styles in the legends on the top right of each panel; these data are compared to the SMDS case of extended AC (no capture). Also shown are the sensitivity limits for various deep field surveys compiled in Oesch et al. (2011). In Figure 5 we focus on the most sensitive of these surveys, HUDF09².

Similarly, Figure 6 plots the apparent magnitudes as a function of redshift for $10^6 M_\odot$ (left) and $10^7 M_\odot$ (right) dark stars which grew via captured DM (rather than via extended AC). The SMDS formed with capture are harder to detect: since they are hotter their peak output is at lower wavelengths (where Ly- α absorption is worse); in addition their radii are 5-10 times smaller, thus lowering their bolometric luminosities (Freese et al. 2010a). In all cases the vertical dashed line is placed at the minimum redshift where the J band dropout criterion is satisfied.

For SMDS with masses $\leq 10^5 M_\odot$, the predicted fluxes in both the F125W and F160W filters are too low to be seen in HST data; the only way around this would be if the object happened to be gravitationally lensed, as discussed in Zackrisson et al. (2010a). The $10^6 M_\odot$ dark stars can be seen in the F125 (F160) passbands out to redshifts of 9 (11.5) while the $10^7 M_\odot$ dark star would be detectable out to redshifts of 10.5 (13). However, $10^7 M_\odot$ DSs would be too bright to be compatible with HST data: they would be several magnitudes brighter than the HST sensitivity, whereas the observed object is just bright enough to be seen. Thus the observed $z = 10$ candidate in HST cannot be a $10^7 M_\odot$ DS. In addition, if $10^7 M_\odot$ SMDS formed at higher redshifts, we can place strong bounds on the numbers of them that can survive down to $z=10$, where they are not found.

² HUDF09 has a limiting 5σ mab of 29.3 in the J-band for an exposure time of 94500 s and 29.4 in the H-band for an exposure time of 146711 s for the H_{160} band.

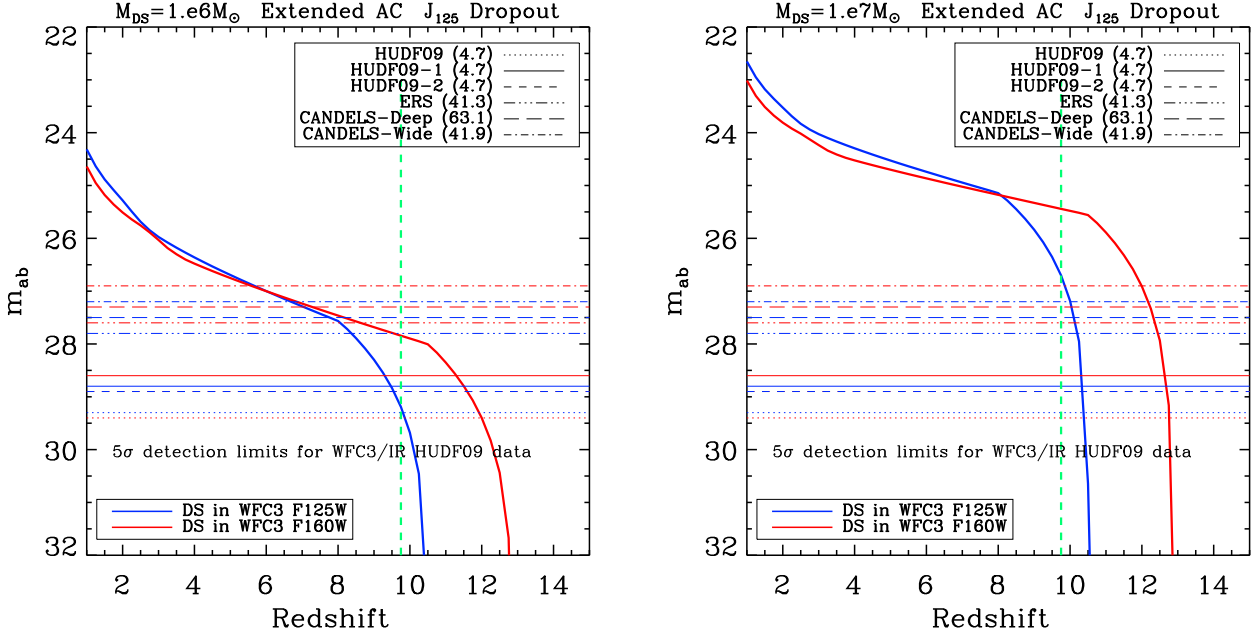


Figure 4. SMDS in HST. Left (right) panels: Thick curves show apparent magnitudes in the H-band [F160W, solid red] and J-band [F125W, blue curves] for the $10^6 M_\odot$ ($10^7 M_\odot$) versus the redshift of observation for dark star formed via extended adiabatic contraction in a $10^7 M_\odot$ ($10^8 M_\odot$) halo at redshift of 15. Thin horizontal lines indicate the 5σ detection limits of the various deep field surveys compiled by Oesch et al. (2011), with the areas of the surveys in arcmin² indicated in the legends. The deepest survey to date is HUDF09 (lowest dotted horizontal lines). The vertical dashed line is placed at the minimum redshift where the J band dropout criterion is satisfied ($z \sim 10$).

We also note that any SMDS that continued to exist to $z=6$ would have been seen as an i_{775} dropout in HUDF which has a $29.9 m_{AB}$ detection limit for 10σ detection in the i_{775} passband (Bouwens et al. 2006). Since no candidates exist in the data, this makes it clear that SMDS did not survive to $z=6$. Thus we conclude that it is the $10^6 M_\odot$ SMDS that serve as the best possible explanation for the J-band dropout at $z=10$ seen by HST.

4.2 Using HST observations to constrain the numbers of dark stars

We will use HST data to constrain the fraction $f_{\text{SMDS}}(z_{\text{start}})$ of early DM halos that can host SMDS. We focus on SMDS of masses $M_{\text{DS}} = 10^6 - 10^7 M_\odot$ since lower mass DS are not observable in current HST data (unless they are significantly magnified by gravitational sensing or if they form clusters of dark stars (Zackrisson et al. 2010b)).

Following Zackrisson et al. (2010b, 2011b), we compute the number N_{obs} of DS that could potentially be observed,

$$N_{\text{obs}} = \frac{dN}{dz d\theta^2} f_{\text{SMDS}}(z = z_{\text{start}}) \theta^2 f_{\text{surv}} f_{\Delta t} \quad (9)$$

and use the fact that at most one object has been observed with HST at $z=10$ to obtain bounds on $f_{\text{SMDS}}(z_{\text{start}})$, the fraction of DM halos in a given mass range that can host a DS:

$$N_{\text{obs}}^{\text{HST}} < 1 \quad (10)$$

Here $dN/dz d\theta^2$ is the number of DM halos forming per unit redshift per arcmin² in which a given mass DS is hosted

(computed from Figure 2). We have multiplied by unit redshift interval $\Delta z = 1$, since we only consider SMDS formed within a redshift interval equal to one (see the discussion following Eqn. (1)). Here θ^2 is the total area surveyed in which the SMDS could have been detected, f_{surv} is the fraction of DS that survives from the redshift where the DS starts forming, z_{start} , until it could be observed as a dropout (at $z \sim 10$ with HST) and $f_{\Delta t}$ is the fraction of the observational window of time Δt during which the DS is still alive. Here, Δt is the cosmic time elapsed between the minimum and maximum redshift where the DS could be observed as a dropout. Please note that those redshifts are different from z_{min} and z_{max} defined under Equation 4. For the case of HST, we get $\Delta t = 6.5 \times 10^7 \text{yr}$ (the cosmic time between the minimum redshift of 9.5 and maximum redshift of 10.5 where the DS could be observed as a J-band dropout computed using Equation 5).

We estimate the survey area θ^2 in the following way: For each of the surveys in Figs. 4 and 6, we have indicated (in parentheses in the plots) the area (in arcmin²) observed by the survey. For DS of a given mass, we can add up the areas of all those surveys which are capable of observing DS as J-band dropouts to obtain a total effective area of observability for that DS mass. In other words, we add the area of all surveys in which the fluxes in the H_{160} are still above the sensitivity limits while the fluxes in the J_{125} are a least 1.2 lower in apparent magnitude and below the detection limit of the J-band. From Figure 4 we estimate $\theta^2 = 4.7 \times 3 \text{ arcmin}^2$ as the effective area of the surveys in which a $10^6 M_\odot$ SMDS formed via extended AC could have been observed as a J band dropout with HST, since its only for the three deepest surveys, each with an area of 4.7

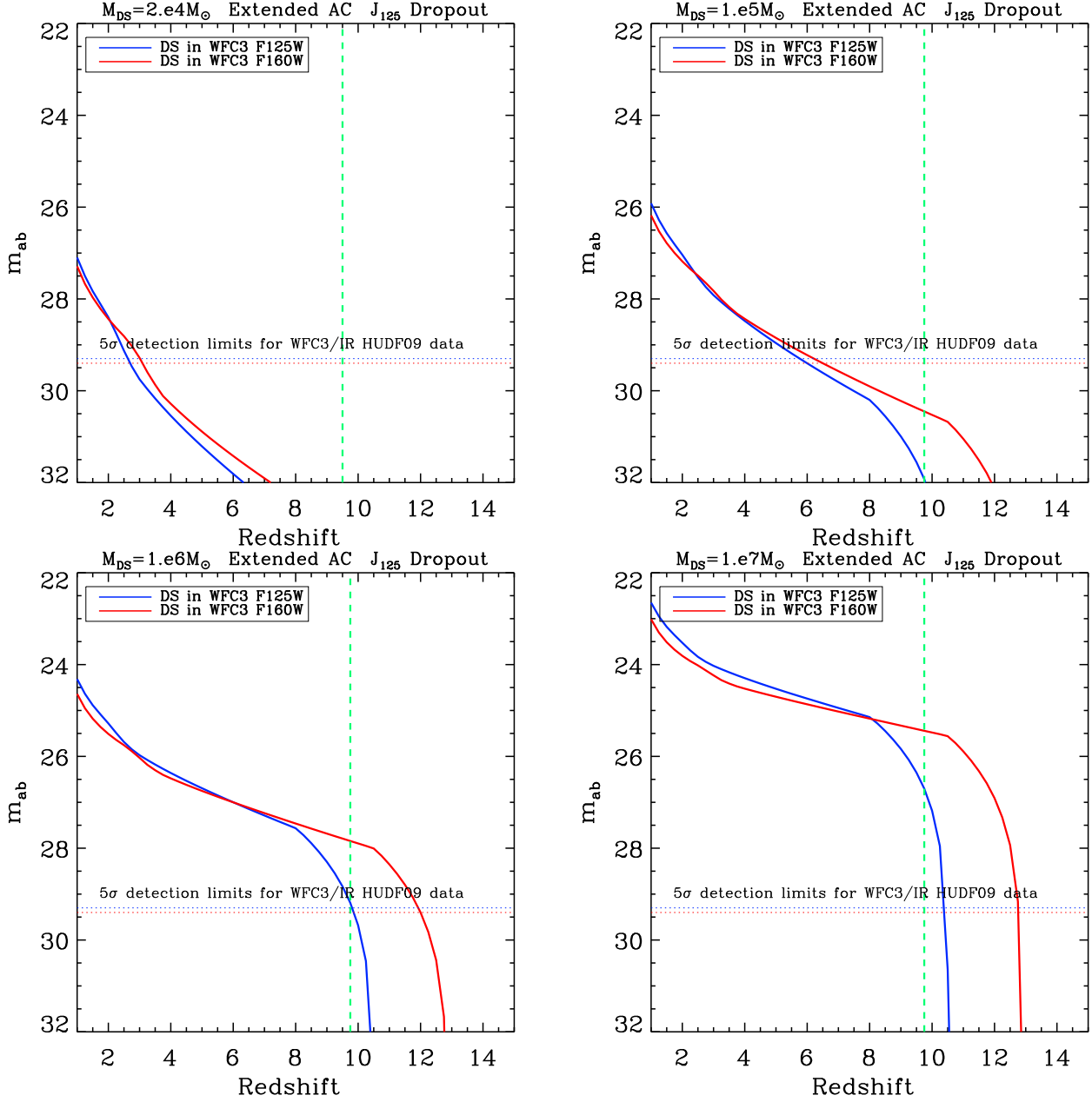


Figure 5. SMDS in HST: J_{125} (blue, F125W) and H_{160} (red, F160W) apparent magnitudes M_{AB} for Dark Stars of mass ranging between $\sim 10^4 M_{\odot} - 10^7 M_{\odot}$ as a function of redshift for WFC3 filters. Here the Dark Stars are considered to be formed via the extended adiabatic contraction mechanism, without any captured DM. The dashed horizontal lines represent the sensitivity limits for the deepest survey available, HUDF09. For the H band the 5 σ depth is 29.4 whereas for the J band it is 29.3. The exposure times are $\sim 9.45 \times 10^4$ s for the J_{125} field and $\sim 1.47 \times 10^5$ s for the H_{160} field. The green vertical line corresponds to the lowest redshift where the dropout criterion is satisfied. Compared to Figure 4 now we explore a wider mass range for the SMDS. Note that SMDS of mass $10^5 M_{\odot}$ or lower cannot be observed as J band dropouts with current HST data (another factor of 100 in observing time would be required) whereas heavier SMDS can be detected.

arcmin², that this SMDS would show up as a dropout. For the $10^6 M_{\odot}$ SMDS formed via captured DM the detectability is much lower, implying that they could have been observed with HST WFC3 as a J band dropout only in the deepest survey, namely in HUDF09, which has an area of 4.7 arcmin².

Although the $z=10$ J-band dropout seen by HST cannot be a $10^7 M_{\odot}$ SMDS (as it would be too bright and would

show up in both bands), still we can apply Eq. (9) to place an upper bound the numbers of these objects. For the $10^7 M_{\odot}$ stars formed via extended AC, this area is increased to ~ 160 arcmin², as all surveys compiled could pick this object up as a J band dropout. For the hotter DS fueled by captured DM, we can see from Figure 6 that the total area of the surveys in which $10^7 M_{\odot}$ DS could have been detected is

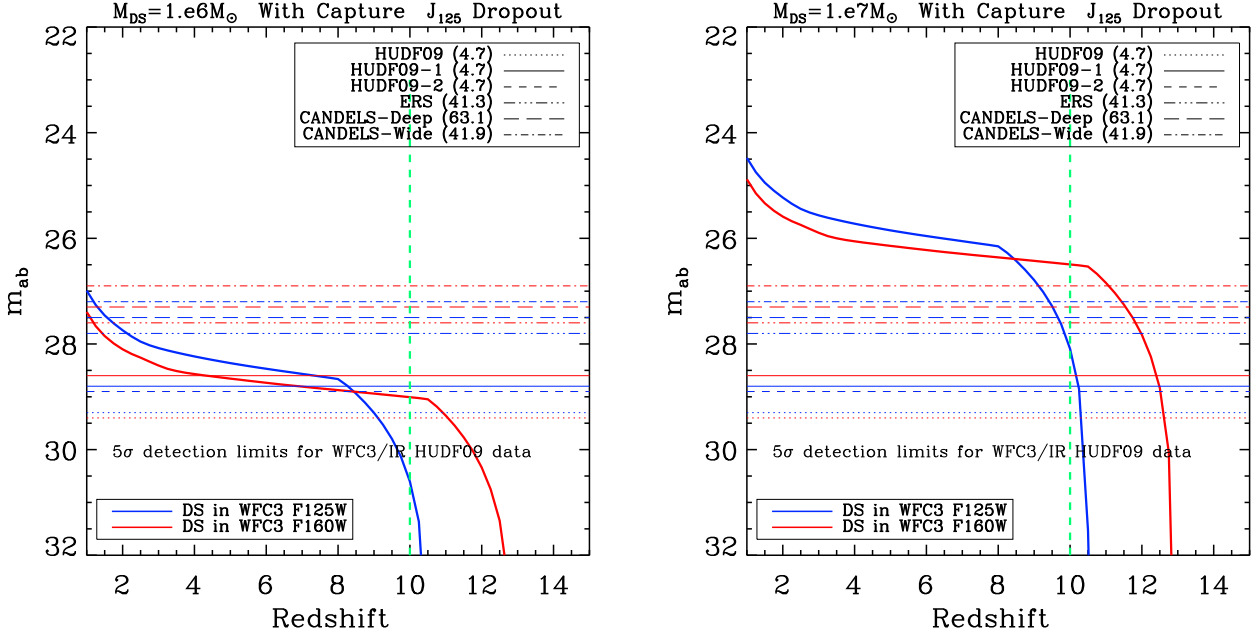


Figure 6. SMDS in HST: Same as Figure 5 but for $10^6 - 10^7 M_\odot$ Dark Stars fueled by captured DM. The dashed horizontal lines represent the sensitivity limits for the deepest survey available, HUDF09.

$\sim 160 \text{ arcmin}^2$ (similar with the area for the extended AC DS of the same mass).

We comment here on the three redshifts of formation we have chosen. For a conversion between z_{form} (redshift where the DS reaches its final mass) and z_{start} (the redshift where the DS starts accreting baryons) see Table 1.

- Case A: $z_{\text{form}} = 10$. Here, we assume that the DS become supermassive only at $z=10$ and not before. We can only constrain the product $f_{\text{SMDS}} \times f_{\text{surv}} \times f_{\Delta t}$. The fraction of the observational window during which the DS is alive and can be observed, is $f_{\Delta t} = \min(\tau - \tau_{\text{min}}, \Delta t) / \Delta t$, where τ_{min} is the minimum DS lifetime that allows the DS to survive to $z = 10.5$ where it can be observed as a J-band dropout with HST. In the case of a $10^7 M_\odot$ SMDS $\tau_{\text{min}} \sim 1.15 \times 10^8 \text{ yrs}$ (time elapsed between $z = 13$ and $z = 10.5$) whereas for the $10^6 M_\odot$ SMDS $\tau_{\text{min}} \sim 3.6 \times 10^7 \text{ yrs}$ (cosmic time elapsed between $z = 10.7$ and $z = 10.5$). We note that the limits we place on $f_{\text{SMDS}}(z_{\text{start}})$ are only valid at $z_{\text{start}} \sim 13$ (for the $10^7 M_\odot$ SMDS) and $z_{\text{start}} \sim 11$ (for the $10^6 M_\odot$ SMDS) as can be seen from Table 1.

- Case B: $z_{\text{form}} = 12$. Here we consider the DS to become supermassive at $z_{\text{form}} \sim 12$ and not at later redshifts. We will assume that the DS could survive until $z \sim 10$ ($f_{\text{surv}} = 1$) in order to constrain $f_{\text{SMDS}}(z_{\text{start}})$ using null detection from HST J_{125} dropouts. From Table 1 we see that the z_{start} value for the $10^7 M_\odot$ SMDS in this case is ~ 16 and for the $10^6 M_\odot$ SMDS it is ~ 13 . In the case of a $10^7 M_\odot$ SMDS $\tau_{\text{min}} \sim 2.0 \times 10^8 \text{ yrs}$ whereas for the $10^6 M_\odot$ SMDS $\tau_{\text{min}} \sim 1.1 \times 10^8 \text{ yrs}$.

- Case C: $z_{\text{form}} = 15$. Here we assume the dark stars become supermassive by $z_{\text{form}} \sim 15$. The values for z_{start} can be read off from Table 1 again. For the $10^7 M_\odot$ SMDS $z_{\text{start}} \sim 22$ and for the $10^6 M_\odot$ SMDS $z_{\text{start}} \sim 16$. This case is treated in a similar fashion as case B. For the $10^7 M_\odot$ SMDS, $\tau_{\text{min}} = 2.9 \times 10^8 \text{ yrs}$ (the time elapsed be-

tween redshifts 22 and 10.5) whereas for the $10^6 M_\odot$ SMDS $\tau_{\text{min}} = 2.0 \times 10^8 \text{ yrs}$ (the time elapsed between redshifts 16 and 10.5).

From Eqn. (9), we obtain the following bounds for $10^7 M_\odot$ SMDS formed via either extended AC or with capture in each of the three cases (A-C):

$$\log f_{\text{smds}}(M_{\text{DS}} = 10^7 M_\odot) \leq \begin{cases} -4.5 - \log(f_{\text{surv}} \times f_{\Delta t}), & \text{A} \\ -3.4 - \log(f_{\text{surv}} \times f_{\Delta t}), & \text{B} \\ -2.1 - \log(f_{\text{surv}} \times f_{\Delta t}), & \text{C} \end{cases} \quad (11)$$

For $10^6 M_\odot$ SMDS formed via extended AC we get the following limits:

$$\log f_{\text{smds}}(M_{\text{DS}} = 10^6 M_\odot) \leq \begin{cases} -4.8 - \log(f_{\text{surv}} \times f_{\Delta t}), & \text{A} \\ -4.6 - \log(f_{\text{surv}} \times f_{\Delta t}), & \text{B} \\ -3.8 - \log(f_{\text{surv}} \times f_{\Delta t}), & \text{C} \end{cases} \quad (12)$$

The values of z_{start} that correspond to these values of z_{form} can be found in the last three rows of Table 1. The reason that the bounds on the numbers of $10^6 M_\odot$ SMDS are tighter than those on the $10^7 M_\odot$ SMDS is the following. In order to reach a larger mass, the DS had to start forming at an earlier redshift and in larger halos; but the numbers of larger halos that can host DS is smaller at higher redshifts. Similarly, the bounds in Case A are ~ 10 (~ 300) times stronger than the bounds in Case C for the $10^6 M_\odot$ ($10^7 M_\odot$) SMDS. Again the reason for the very large discrepancy ~ 300 is the fast decrease of the formation rate of $1 - 2 \times 10^8 M_\odot$ DM halos at redshifts higher than $z \sim 15$ as can be seen from Figure 2. For SMDS lighter than $10^6 M_\odot$ HST cannot be used to place constraints, as those objects are not detectable with HST as J-Band dropouts. A summary of our bounds can be found in Figure 7 where we plot the exclusion limits for f_{SMDS} .

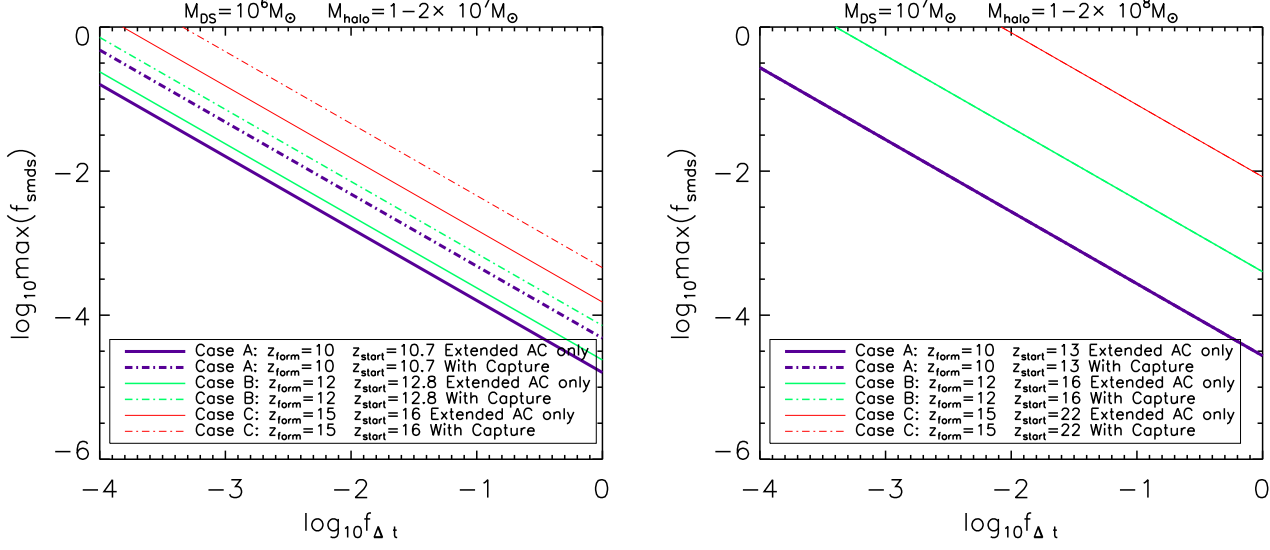


Figure 7. Upper bounds from HST on the fraction f_{SMDs} of early halo hosting dark stars of masses as labeled above the plots; values above the lines are excluded. Different lines correspond to different values of the redshift ($z_{\text{form}} = 10, 12$, and 15) at which the DS attains this mass; see Table 1 for the connection between (a) the redshift z_{start} at which the DS came into existence and started to grow and (b) the redshift z_{form} at which it reached the supermassive size as labeled. This plot assumes $f_{\text{surv}} = 1$ (i.e. the DS survives long enough to reach the redshift window of observability as a J_{125} dropout with HST). However, the DS need not survive throughout the entire window; in fact the horizontal axis in both plots is $\log_{10} f_{\Delta t}$, for which a value of 0 corresponds to the DS lifetime being sufficiently large that it survives throughout the redshift window of observability. Solid lines correspond to DS formation via extended AC (without capture) while dashed lines correspond to DS formation via capture. Since DS less massive than $10^6 M_{\odot}$ are too faint to be detected by HST, these data do not bound f_{SMDs} for lower mass dark stars.

4.3 Other Bounds on Numbers of SMDs

Further bounds on the numbers of DS and the halos they form in should result from a variety of considerations. One would be the contribution to reionization. Work of Venkatesan (2000) studied stellar reionization with the standard fusion powered first stars (Population III), without any dark stars. From comparison with the optical depth to last scattering from early WMAP data, she bounded the fraction of baryons in halos that can cool and form stars (assuming a Scalo initial mass function) to be in the range $f_{*} \sim 0.01-0.1$. However, it is not clear how these numbers would change in the presence of DS and with the updated value for the optical depth from WMAP7 (Komatsu et al. 2011).

More recently, the effects of DS (and the resultant main sequence stars) on reionization was studied by Schleicher et al. (2008, 2009) and Scott et al. (2011). While DS are fully DM powered, they remain so puffy and cool that no ionizing photons are produced, and there is no contribution to reionization. However, once the DM fuel begins to run out, they contract and heat up as they approach the zero age main sequence (ZAMS) with the onset of fusion, at which point they do produce ionizing photons. For the case of extended AC, and for DS less massive than $1000 M_{\odot}$, Scott et al. (2011) concluded that the reionization history of the Universe is unaffected by the DS, compared to the case of more standard Pop III stars: the DS period of no ionizing photon production is compensated by a short period of high ionizing photon production during approach to the ZAMS. However, we are not sure what the effect on reionization would be in the case of the more massive SMDs. On the one hand the more massive stars are hotter and brighter and would emit substantial amounts of ionizing photons; on

the other hand the more massive the star, the shorter the lifetime.

For the case of DS with high capture rates, previous studies Scott et al. (2011) find that reionization is somewhat delayed, decreasing the integrated optical depth to the surface of last scattering of the CMB. However, variation of astrophysical parameters for the case of standard reionization with standard Pop III stars can produce exactly the same effect, so that disentangling these effects will prove difficult. Nonetheless Scott et al. (2011) do argue that they can rule out the section of parameter space where dark stars $\sim 1000 M_{\odot}$ with high scattering-induced capture rates tie up more than 90% of all the first star-forming baryons and live for more than 250 Myr. Again, their work should be extended to the heavier SMDs we study in this paper.

A complicating factor (for both the cases of extended AC and capture) is that the SMDs do eventually collapse to BH, and it's not clear how rapidly that happens. If the collapse to BH is rapid, this may cut short the ZAMS phase and reduce the role SMDs play in reionization. Second, the SMDs are likely to have stellar pulsations (Montgomery et al. 2011, in progress); as a consequence it is possible they will lose some mass before reaching the ZAMS. Third, even after joining the ZAMS, en route to BH collapse, the SMDs may blow off some of their mass (Umeda et al. (2009) suggest 1/2 of their mass).

Alex Heger (private communication) has the following new results for early stars (only made of hydrogen and helium) that are nonrotating: If they are heavier than $153,000 M_{\odot}$, no hydrostatic equilibrium solution exists, i.e. no primordial hydrogen burning star exists. Thus once a fusion powered star accretes enough mass to get heavier than this,

then it collapses straight to a BH. For any of our dark stars that are heavier than this, once they run out of DM, they collapse directly to BH without contributing at all to reionization. Rotation might change these results.

Further, there are implications of DS regarding the fraction of baryons that end up in DSs. Our work assumes that the DS can grow in a DM halo of a given mass until almost all the baryons in the halo (assumed to be the baryonic mass fraction in the Universe) are accreted onto the DS. If the total fraction of halos in which such DSs form is too large, this implies that most of the baryons in the Universe are trapped inside DS and it is not clear how they would contribute any further to galaxy formation. As mentioned above, en route to BH collapse, the SMDS may blow off some of their mass, reinjecting baryons into the surrounding halos and alleviating this problem somewhat.

Further bounds on the numbers of dark stars have been studied in Sandick et al. (2011). The remnant black holes from the DS should still exist today, including inside the Milky Way. They still have enhanced amounts of DM around them, known as DM spikes. The DM inside the spikes annihilates to a variety of final products, with γ -rays that would be detected by the Fermi Gamma Ray Space Telescope (FGST). In Sandick et al. (2011), it was noted that most of the 368 point sources observed by FGST might in fact be due to DM annihilation in the spikes. In addition, FGST data were used to place bounds on the fraction of early haloes hosting DS to avoid overproduction of gamma-rays from annihilation in the remnant DM spikes. The bounds range from $f_{DS} < 10^{-3} - 1$, depending on the WIMP mass and annihilation channel.

All of these considerations are beyond the scope of this paper. For now we take these arguments to imply that not every early halo can contain a DS.

5 OBSERVING SUPERMASSIVE DARK STARS WITH JWST

Dark stars can be detected by upcoming James Webb Space Telescope (JWST). Table 2 gives a summary of the sensitivity of the NIRCам and MIRI cameras on JWST in various wavelength bands³. One can see that the NIRCам is much more sensitive than the MIRI filters, so that light emitted at wavelengths larger than 5 microns is harder to observe. In this section we estimate the number of SMDS that would show up in a typical survey with JWST NIRCам or MIRI cameras, based on the bounds we have just derived in the previous section.

Figures 8 - 11 illustrate the detectability of SMDS with

JWST NIRCам filters. Figures 8 and 9 plot the stellar spectra of SMDSs of various masses and formation redshifts as a function of wavelength (for light emitted at $z = 15, 10$ and 5) and compare to the sensitivity of JWST filters for 10^4 s and 10^6 s exposure times. In Figures 10 and 11, we instead plot the apparent magnitudes as a function of redshift of emitted light for various SMDS through the NIRCам camera wide passband filters, with each panel in the figure focusing on a particular JWST broadband filter; in these two figures the SMDS are formed via extended AC and capture respectively. Ly- α absorption cuts off the photons with wavelengths lower than 1216Å (in the rest frame); we treat the absorption as being complete. Thus the SMDSs drops below the JWST sensitivity limit at $z \sim 6$ for the F070W filter and at $z \sim 10$ for the F115W case.

Since the most massive dark stars are the brightest, they are the easiest to detect. From figures 10 and 11 one can see that $10^7 M_\odot$ dark stars, both with and without capture, are individually observable in 10^4 seconds of NIRCам data even at redshifts as high as 15 in filters with a passband centered at 2 μ m and higher (F200W-F444W filters). For the case of a $10^6 M_\odot$ SMDS, a longer exposure time of 10^6 s allows the dark star, both with and without capture, to be individually observable in all filters from F200W to F444W even at $z \sim 15$. For $10^5 M_\odot$ SMDS, those formed via extended AC are visible in these filters out to $z \sim 15$ with 10^6 sec exposure time while those formed with capture are too dim. Lighter ones $< 10^5 M_\odot$ would not be detectable as J-band dropouts but, if they survived to lower redshifts (e.g. $z=7$) would likely already have been seen with HST or other telescopes. Since the sensitivity of the higher wavelength MIRI filters above 5 μ is worse, only the $10^7 M_\odot$ DS are bright enough to be observable in MIRI filters (see the discussion of Figure 15 in Section 6).

5.1 Detection at $z \sim 10$ as a J_{115} band dropout with JWST

As expected, the dark stars that could have been detected as J-band dropouts with HST are also detectable using the same technique with JWST. We again will adopt the same dropout criterion, i.e. $\Delta m_{AB} > 1.2$ in the J and H broadband filters. Figure 12 shows the sensitivity of JWST in a 10^4 exposure in the 1.15 μ (J-band) and 1.50 μ (H-band) filters for NIRCам. The apparent magnitudes for 10^6 and $10^7 M_\odot$ SMDS with and without capture are also shown for comparison. Here, the SMDS form at $z=15$ and are assumed to survive to various redshifts as shown. Comparing Figures 4 and 12 (see also Table 2), one can see that JWST is about half a magnitude more sensitive than HST to finding SMDS as J-band dropouts (for 10^5 s exposure time with numbers provided in the literature as 5σ detection in HUDF09 and 10σ detection with JWST).

The three cases of $10^7 M_\odot$ with or without capture as well as $10^6 M_\odot$ without capture could be detectable in a JWST survey as J band dropouts in the redshift range 9.5 - 12 even with the lower 10^4 second exposure times. The $10^6 M_\odot$ Dark Star formed via captured DM (lower left plot) in Figure 12 will require a longer exposure time of 10^6 s (which would correspond to the same exposure time as the 2004 HUDF survey).

In order to predict how many SMDS would be visible

³ Specifically we show the 10σ required m_{AB} sensitivities for the NIRCам and MIRI wide filters after 10^4 seconds exposure derived based on the limiting fluxes published at <http://www.stsci.edu/jwst/instruments/miri/sensitivity/> and http://www.stsci.edu/jwst/instruments/nircam/sensitivity/table*. One can scale the limits to different exposure times, as the limiting flux $\propto t_{exposure}^{-1/2}$ and converting to m_{AB} magnitudes is just a matter of applying Equation 7. For instance an increase by a factor of 100 in exposure times would convert in a gain in the sensitivity limits by 2.5 AB magnitudes.

	Filter	$\lambda_{center} (\mu m)$	$\log_{10} \lambda_{center}$	$\Delta\lambda (\mu m)$	m_{AB}
NIRCam	F070W	0.7	-0.15	0.175	28.1
	F090W	0.9	-0.05	0.225	28.51
	F115W	1.15	0.06	0.2875	28.72
	F150W	1.5	0.17	0.375	28.77
	F200W	2.0	0.30	0.5	28.75
	F277W	2.77	0.44	0.6925	28.67
	F356W	3.56	0.55	0.89	28.55
	F444W	4.44	0.65	1.11	27.92
MIRI	F560W	5.6	0.75	1.2	25.65
	F770W	7.7	0.89	2.2	25.28
	F1000W	10.0	1.00	2.0	24.29
	F1130W	11.3	1.05	0.7	23.32
	F1280W	12.8	1.1	2.4	23.53
	F1500W	15.0	1.18	3.0	23.26
	F1800W	18.0	1.25	3.0	22.31
	F2100W	21.0	1.32	5.0	21.56
	F2550W	25.5	1.4	4.0	20.28

Table 2. 10σ sensitivity limits for the JWST wide passband filters (fourth column). The m_{AB} limits are derived assuming 10^4 seconds exposure and are based on the limiting fluxes published at <http://www.stsci.edu/jwst/instruments/miri/sensitivity/> and http://www.stsci.edu/jwst/instruments/nircam/sensitivity/table*. We identify each filter by its name, in the first column. Values in the second column correspond to the center wavelength of each filter, whereas in the fourth column the values for the passband width are given.

in a JWST deep field survey we have to assume something about the total field of view (FOV) of all future JWST surveys in which the stars would be observable. The FOV of the NIRCam instrument is $2.2' \times 4.4' = 9.68 \text{ arcmin}^2$ (see <http://www.stsci.edu/jwst/overview/design/>) This value is likely to be an underestimate. Since HST had multiple surveys with a total of 160 arcmin^2 , we will also consider the case of multiple surveys with JWST with a total added area of $\sim 150 \text{ arcmin}^2$. Given the bounds on the numbers of DS from HST from the previous section, we find that the number of expected SMDS with JWST as J-band dropouts is $N \lesssim 1$ and therefore conclude that SMDS are hard to detect with JWST as J-band dropouts. This is expected since HST was already sensitive enough to observe them as J-band dropouts, assuming enough would have survived from their formation redshift until $z \sim 10$. The only improvement could be made by a larger survey area compared to the one with HST. For the $10^6 M_\odot$ SMDSs formed with capture, which were detectable only in the 4.7 arcmin^2 of HUDF09, JWST should be able to provide a larger survey area so that these objects become more detectable.

5.2 Detection at $z \sim 12$ as a H_{150} band dropout with JWST

Whereas JWST is not particularly better than HST at finding J-band dropouts, it will be significantly better at finding SMDS as H-band and K-band dropouts at higher wavelengths. In this section we focus on H-band dropouts, where the object can be seen in the F200 NIRCam filter of JWST but not in the F150 NIRCam filter. As before in Eqn. (6), we require the difference between the broadband fluxes in the H_{150} and K_{200} filters to be greater than 1.2 AB magnitudes. We see that the SMDS stellar light seen with JWST's K_{200} filter is essentially unaffected by Ly- α absorption until $z \sim 15$, whereas the IGM absorption will cut off most

of the flux in the H_{150} at $z \gtrsim 11.5$. (see Figure 13). Hence SDMS can appear as H-band dropouts.

We will consider the case of SMDS forming at $z_{\text{form}} = 12$, the same as the time of observation. Figure 13 shows that the three cases of $10^7 M_\odot$ SDMSs with and without capture as well as $10^6 M_\odot$ SMDSs without capture are all detectable in a JWST survey as H_{150} dropouts in the redshift range $11.5 - 12.5$. DS formed at higher redshifts could be seen all the way out to $z \sim 14, 15$, but likelihood analyses on any objects found as H-band dropouts with photometry with JWST will probably estimate the redshift at $z \sim 12$. The $10^6 M_\odot$ Dark Star formed via captured DM (lower left plot) is too faint to appear as a dropout. The number of H_{150} dropout events is given by Eq. (9) with $\Delta z = 1$ and $f_{\text{surv}} = 1$ since the objects are observed at the same time they form) and the appropriate survey area θ^2 for JWST must be applied.

Is it reasonable to apply the bounds from HST on the numbers of SMDS at $z=10$ to those at $z=12$? We will consider three different possibilities, and summarize all results for the predicted number of H band dropouts with JWST in Table 3. If we assume that all the SMDS at $z=12$ have the same properties as those at $z=10$, and that they survive throughout the redshift window observable by HST, then the HST bounds are so stringent that JWST will not be able to see many of them. This is the case we label "Maximal Bounds". In particular, $10^7 M_\odot$ SMDSs would have been so bright as to be easily seen in HST, and the resultant stringent bounds imply that only $N_{\text{obs}} \sim 1$ DS would be found even with multiple surveys with 150 arcmin^2 FOV. For $10^6 M_\odot$ SMDSs the bounds from HST are slightly weaker because the objects are not as bright, so that 10 (32) of these might be found per 150 arcmin^2 field for DS that grew via extended AC (with capture). Since the ones with capture are fainter and harder to see, (counterintuitively) the weaker HST bounds imply that more of them might be found with JWST.

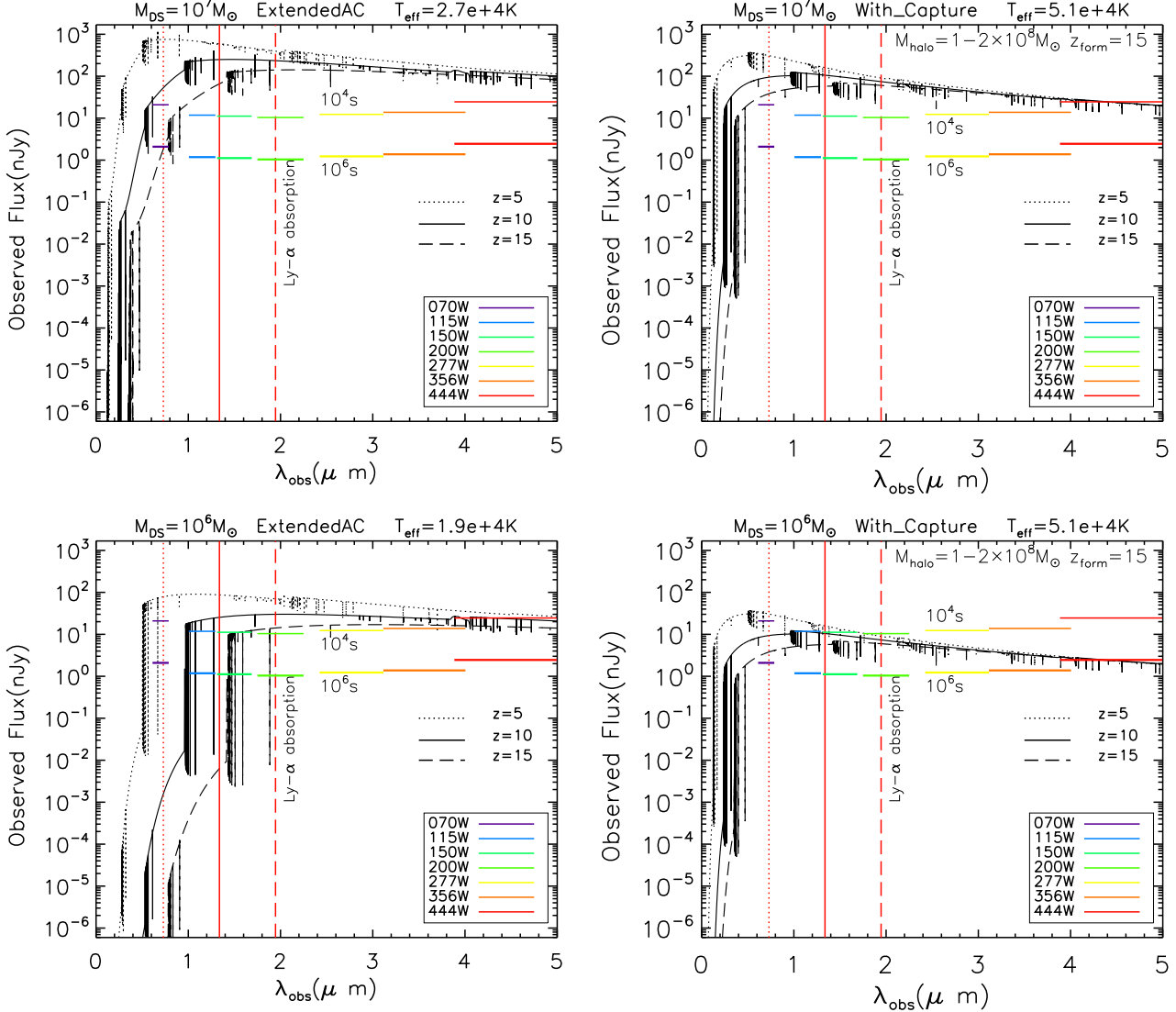


Figure 8. Spectra for supermassive dark stars formed at $z_{\text{form}} = 15$ compared with sensitivity of JWST filters. Listed above each panel are the mass of the DS in solar masses, the formation mechanism (extended AC or “with capture”) and the surface temperature T_{eff} . The fluxes are shown at $z = 15$ (dashed line), 10 (solid line) and 5 (dotted line) and compared to the detection limits of Nircam wide passband filters. The colored horizontal lines represent the sensitivity limits for the filters as labeled in the legend for exposure times 10^4 s (upper lines) and 10^6 s (lower lines). IGM absorption will decrease the observed fluxes for wavelengths shortward of the vertical red lines, which indicate the Ly- α line (1216\AA) redshifted from the rest-frame of the star.

However, it is very likely that there are more SDMS at $z=12$ (the JWST window) than at $z=10$ (the HST window). For one thing, the host halo formation in this mass range peaks at $z \sim 12$ (see Fig 3). Moreover at lower redshifts ($z \sim 10$) the DM halos that could host those SMDSs are much more likely to merge to form even larger halos. In addition, after the first SDMS die (before $z=10$), they turn into fusion powered stars that produce ionizing photons, which disrupt the formation of DS at lower redshifts. Indeed the strong halo clustering at high redshift would cause the possible formation sites to be preferentially close to or inside the HII regions during reionization, potentially leading to strong suppression of star formation; due to this mechanism Iliev et al. (2007) found a suppression of $10^8 M_{\odot}$ - $10^9 M_{\odot}$ halos by an order of magnitude due to Jeans mass filtering in the ionized and heated H II regions.

We will thus recalculate the number of DSs detectable with JWST using weakened bounds from HST. We will take $f_{\text{SMDS}} f_{\Delta t} f_{\text{surv}} = 1.5 \times 10^{-2}$ as our “Intermediate Bounds” case. This case could imply that not all minihaloes host DS, or that not all DS survive throughout the $z \sim 10$ HST observability window. In this Intermediate Bounds case, hundreds or thousands of SMDS are potentially observable.

For comparison, in the Table we list as a third case the full number of DM haloes that could in principle host DS. If all of these contained DS one would expect up to $\sim 450,000$ DS with JWST. However, as discussed in Section 4.3 this would be extremely unreasonable as there would be no baryons outside of DS left for galaxy formation. Our results for the detectability of SMDS as H-band dropouts with JWST are summarized in Table 3.

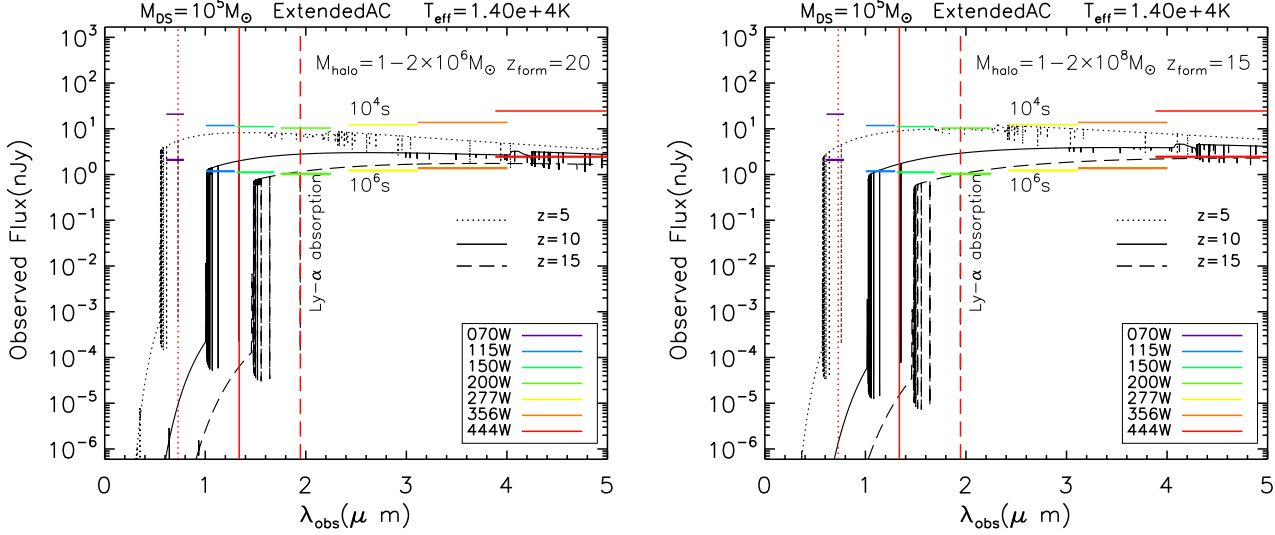


Figure 9. Similar to Figure 8, now for a $10^5 M_\odot$ DS formed either at $z_{\text{form}} = 20$ in a $10^6 M_\odot$ DM halo (left panel) or at $z_{\text{form}} = 15$ in a $10^8 M_\odot$ DM halo (right panel).

Upper limits on numbers of SMDS detectable with JWST as H_{150} dropout				
$M_{DS}(M_\odot)$	Formation Scenario	Bounds from HST	N_{obs}^{FOV}	N_{obs}^{multi}
10^6	Extended AC	Maximal Bounds	$\lesssim 1$	10
10^6	With Capture	Maximal Bounds	2	32
10^7	Any	Maximal Bounds	$\lesssim 1$	~ 1
10^6	Extended AC	Intermediate	45	709
10^6	With Capture	Intermediate	137	2128
10^7	Any	Intermediate	4	64
10^6	Extended AC	Number of DM halos	28700	444750
10^6	With Capture	Number of DM halos	28700	444750
10^7	Any	Number of DM halos	155	2400

Table 3. Upper limits on the number of SMDS detections as H_{150} dropouts with JWST. In first three rows (labeled "Maximal Bounds") we assume that all the DS live to below $z=10$ where they would be observable by HST, and we apply the bounds on the numbers of DS f_{SMDS} from HST data in Section 4.2. The middle three rows (labeled "Intermediate") relax those bounds by assuming that only $\sim 10^{-2}$ of the possible DS forming in $z=12$ haloes make it through the HST observability window. For comparison we also tabulate in the last three rows the total number of potential DM host halos in each case. We also split the number of observations in two categories, N_{obs}^{FOV} and N_{obs}^{multi} . The first assumes a sliver with the area equal to the FOV of the instrument (9.68 arcmin^2), whereas in the second we assume multiple surveys with a total area of 150 arcmin^2 . Note that for the case of the $10^7 M_\odot$ SMDS the predictions are insensitive to the formation mechanism.

5.3 Detection at $z \sim 15$ as a K_{200} dropout with JWST

DS at $z \gtrsim 14$ can be detected as K_{200} band dropouts using the F200 and F277 NirCam filters in JWST, as shown in Figure 14 for 10^6 and $10^7 M_\odot$ SMDS formed via extended AC (no capture) at $z_{\text{form}} = 20$. To qualify as a K_{200} dropout the difference in magnitudes between the F277W and F200W filters must be greater than 1.2. As for the case of H-band dropouts above, we use HST data to bound the number of possible K-band dropouts, under three different assumptions: (i) Maximal Bounds where every DS survives through the HST observability window at $z \sim 10$; (ii) Intermediate Bounds with $\sim 10^{-2}$ of the possible DS surviving that long, and (iii) for comparison simply counting every possible hosting halo. Our results for predicted numbers of SMDS observable as K-band dropouts with JWST are summarized in Table 4

The $10^6 M_\odot$ DS could be observed in the redshift range

$z \sim 15 - 17$ as a K_{200} dropout for 10^4 seconds exposure. For the case of Maximal Bounds from HST, we predict at most $N_{obs}^{multi} \sim 1$. For the Intermediate Bounds case, the possible number of detections is increased to roughly 5 for the case of a 9.68 arcmin^2 FOV or to 75 for the 150 arcmin^2 case. The (unreasonable) case where every possible halo hosts a DS shows the maximal number of $10^6 M_\odot$ SMDS observable as K-band dropouts to be $\sim 70,000$. In the case of the $10^7 M_\odot$ star, it would appear as a K_{200} dropout in the $16 - 20$ redshift range. However due to the sharp drop in the formation rate of DM halos in the $1 - 2 \times 10^8 M_\odot$ at such high redshift the number of dropout events we predict in this case is at most ~ 1 (other than for the unreasonable case where every single possible halo hosts a SMDS). The results for the detectability of SMDS as K-band dropouts with JWST are summarized in Table 4.

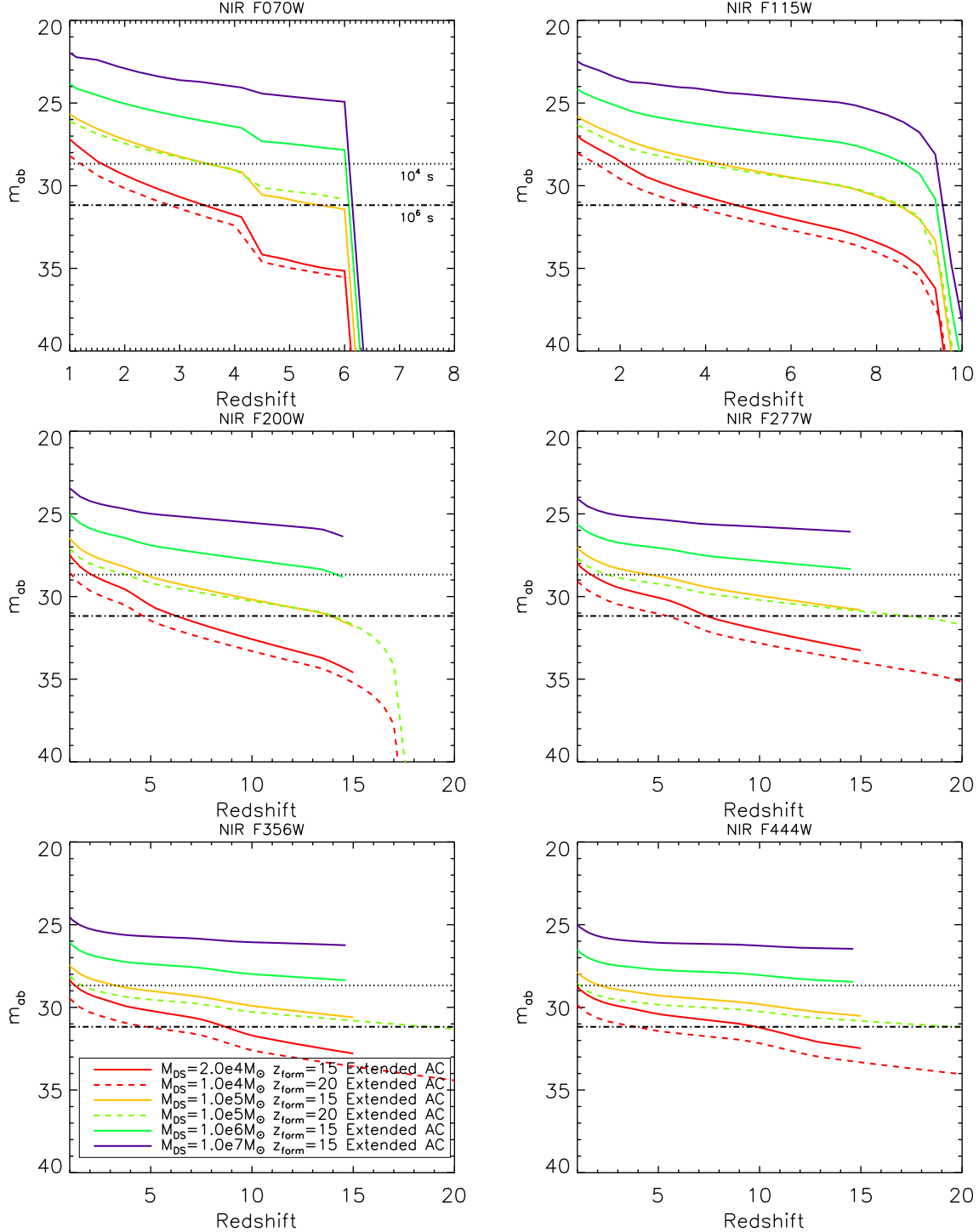


Figure 10. Apparent magnitudes as a function of redshift for various SMDS through the NIR camera wide passband filters on JWST for the case of formation via extended AC. The number after the letter F and before the letter W in the name of each filter corresponds to the wavelength in the center of the passband in 0.01 μm units. The two horizontal lines correspond to sensitivity limits for each filter for 10^4s exposure time (the dotted line) and 10^6s exposure time (the dash-dotted line). The z_{form} labeled in the legend is the formation redshift when the SMDS reached its corresponding mass. The curves corresponding to $z_{\text{form}} = 15$ do not extend all the way to $z = 20$ because at that high redshift the star has not formed yet. The sharp decrease of the fluxes at various redshifts in the first three panels is due to the Gunn-Peterson trough entering the filters. The higher wavelength filters F277W-F444W would not be affected by the IGM absorption until $z \gtrsim 20$.

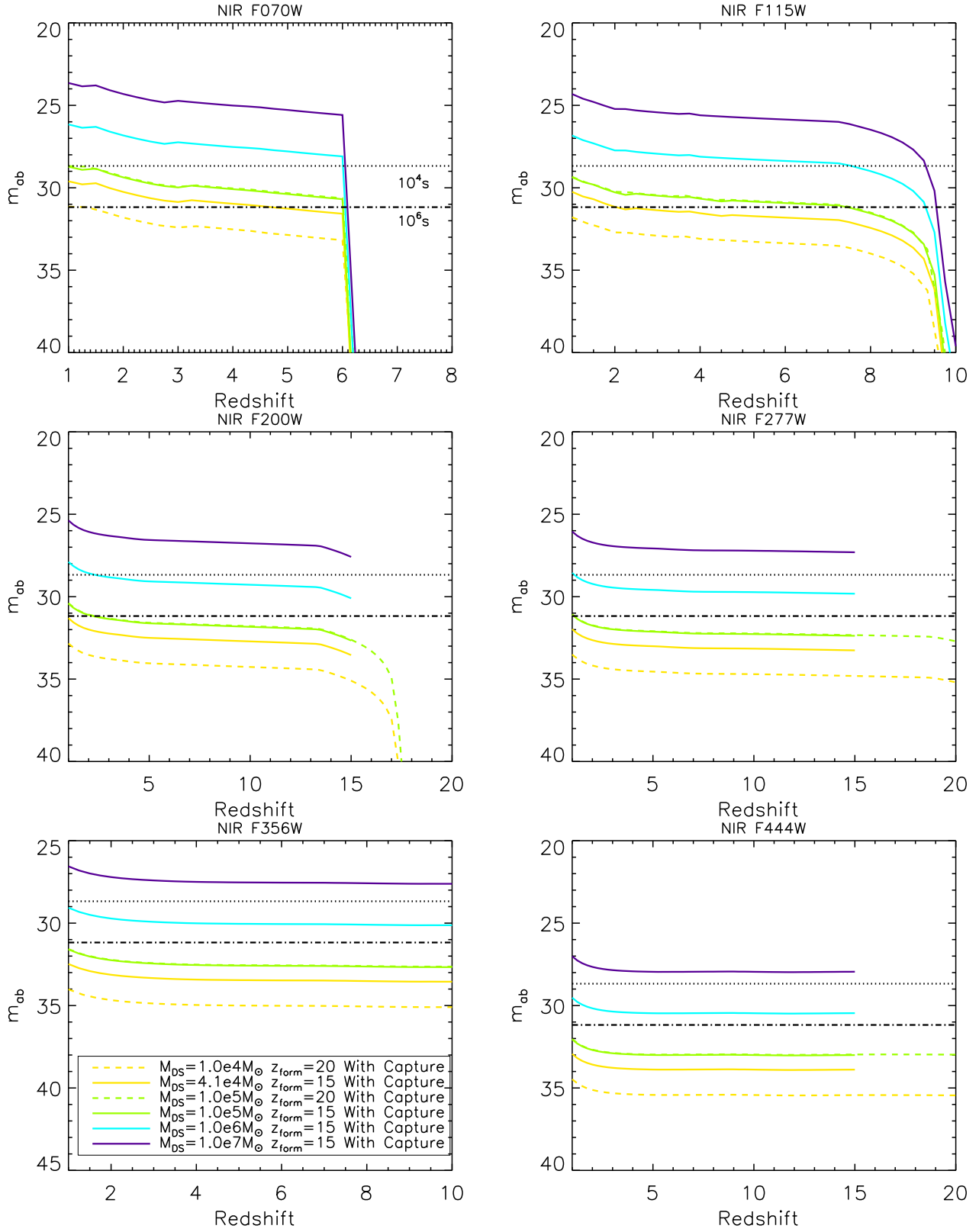


Figure 11. Same as Figure 10 for SMDS formed "with capture" in various JWST bands as labeled.

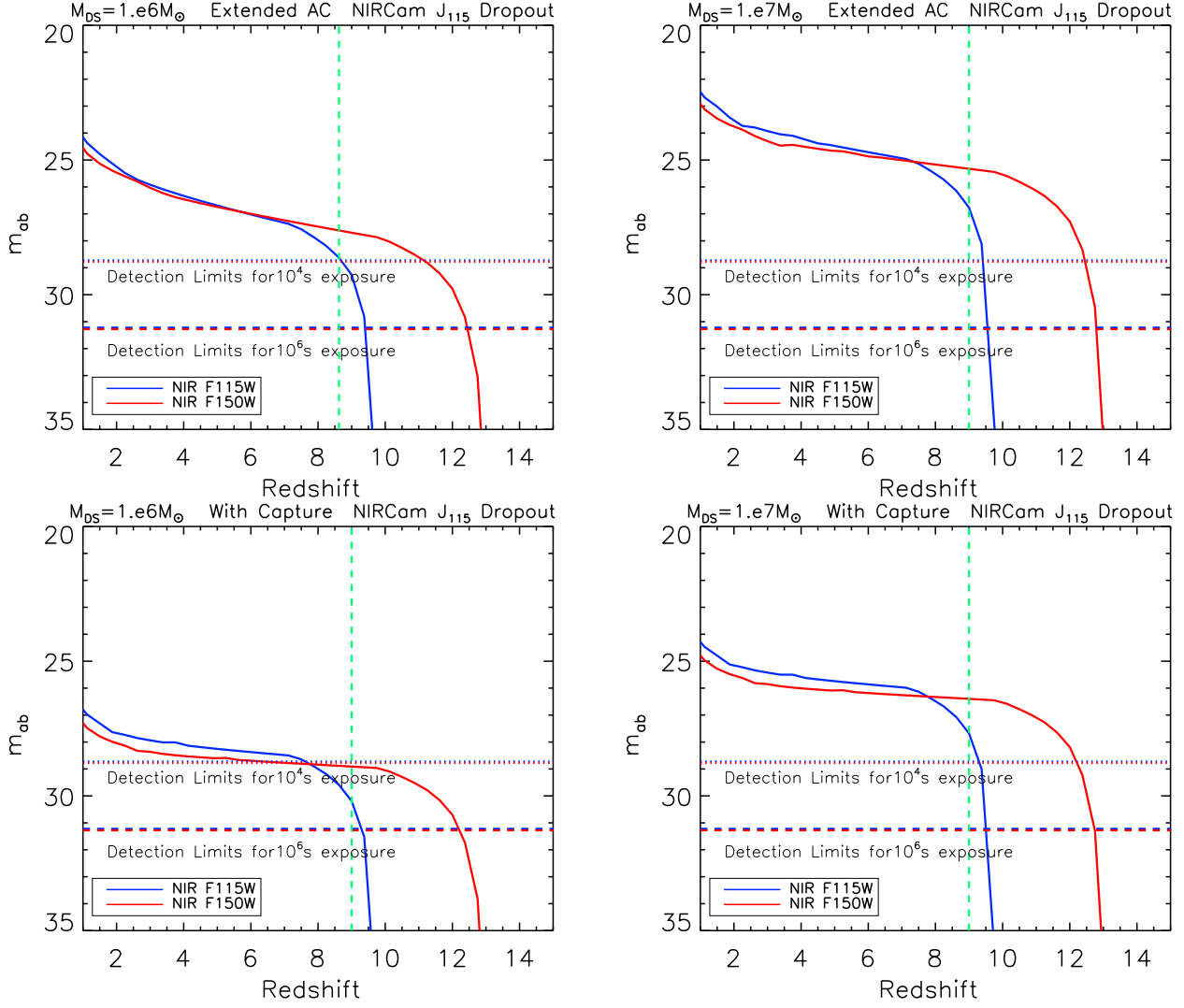


Figure 12. SMDS with JWST as J_{115} band dropouts: Apparent magnitudes for various SMDS through the F115W and F150W filters for NirCam. Top panel: $10^6 M_{\odot}$ and $10^7 M_{\odot}$ Dark Stars formed without DM capture. Lower panel: $10^6 M_{\odot}$ and $10^7 M_{\odot}$ Dark Stars formed “with capture”. The dotted horizontal lines are obtained from the 10σ required sensitivities for 10^4 seconds exposure data published at <http://www.stsci.edu/jwst/instruments/nircam/>; note that the detection limits for the J_{115} and the H_{150} filters differ by only ~ 0.05 m_{AB} apparent magnitude and are thus essentially indistinguishable. The dashed horizontal lines are obtained assuming 10^6 seconds exposure time.

Upper limits on numbers of SMDS detectable with JWST as K_{200} dropout				
$M_{DS}(M_{\odot})$	Formation Scenario	Bounds from HST	N_{obs}^{FOV}	N_{obs}^{multi}
10^6	Extended AC	Maximal Bounds	$\lesssim 1$	~ 1
10^7	Any	Maximal Bounds	$\ll 1$	$\ll 1$
10^6	Extended AC	Intermediate	5	75
10^7	Any	Intermediate	$\ll 1$	$\lesssim 1$
10^6	Extended AC	Number of DM halos	4511	69900
10^7	Any	Number of DM halos	8	116

Table 4. The number of SMDS detections as K_{200} dropouts with JWST. Cases are the same as above in Table 3.

6 SMDS VS POP III GALAXIES WITH JWST

A key question in the discovery of dark stars with JWST will be the ability to differentiate these objects from other sources at high redshifts. Assuming that a population of potential $z > 10$ candidates is identified by the drop out

techniques described in previous sections, the most significant contaminant population at these redshifts is likely to be galaxies dominated by Pop III stars. In this section we focus on ways to differentiate between SMDSs and galaxies containing Pop III stars. Zackrisson et al. (2010a) showed that DSs in the mass range $< 10^3 M_{\odot}$ could be easily distin-

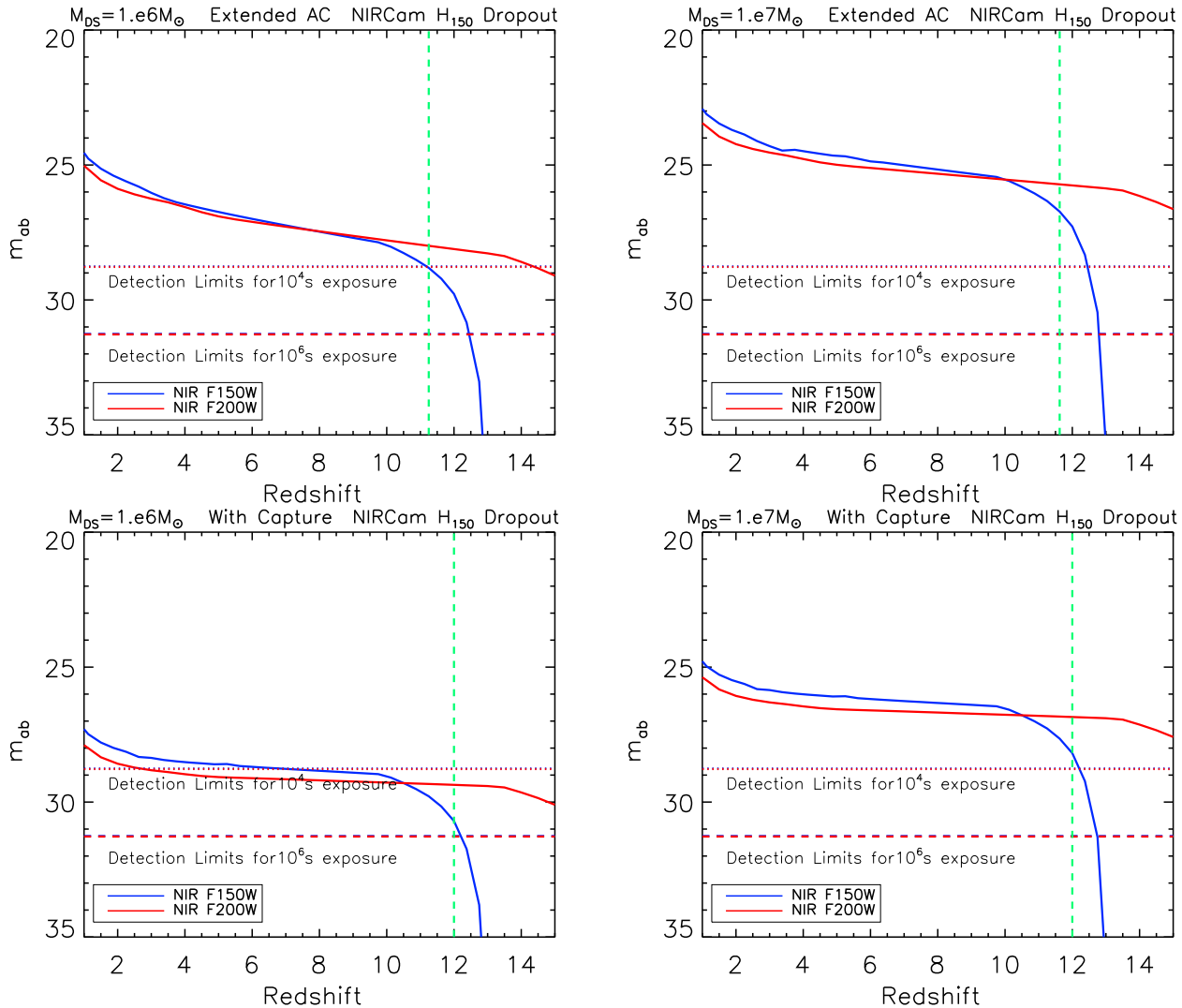


Figure 13. SMDS with JWST as H_{150} band dropouts: Apparent magnitudes for SMDS through the F150W and F200W NirCam filters. Those could be used to establish dropout detection criteria in the 12–14 redshift range. Top panel: cases of interest ($10^6 M_\odot$ and $10^7 M_\odot$) Dark Stars formed without considering DM capture. Lower panel: $10^6 M_\odot$ and $10^7 M_\odot$ Dark Stars formed including DM capture. The vertical green dashed line indicates the minimum redshift at which the DS will appear as a dropout.

guished from galaxies in the redshift range $z = 0 - 15$ (including galaxies containing Pop III stars), supernovae, AGN, Milky Way halo stars as well as Milky Way brown dwarfs by their extremely red colors in color-color plots. The DS considered there have all $T_{\text{eff}} \lesssim 9000K$, which leads to an decrease of the ratio (B) of the fluxes to the left and right of the Balmer jump located at $0.365 \mu\text{m}$ with temperature (see Sec. 8.3 of Rutten 2003). The significant Balmer jump in the case of DS with mass $\lesssim 10^3 M_\odot$ will lead to very red $m_{365} - m_{444}$ colors at $z=10$, offering a distinct signature, as pointed out in Zackrisson et al. (2010a). Here we study instead the much heavier SMDSs with $M_{DS} > 10^5 M_\odot$. These heavier stars are intrinsically much brighter and thus easier to find as dropouts. However, they are also hotter than $10000K$, leading to values of the ratio B to increase with temperature, as explained in Sec. 8.3 of Rutten (2003). For the SMDS we consider here the Balmer jump is insignificant, therefore its much more difficult distinguishing them from potential interlopers based on the technique proposed

in Zackrisson et al. (2010a) for the smaller $\sim 10^3 M_\odot$ DS. In this section we begin a discussion of this issue, restricting our studies to what can be learned from JWST directly. Future studies will be required, in which we investigate also the possible role of spectroscopy with TMT and GMT, and other upcoming observatories in differentiating Pop III galaxies from dark stars.

The earliest Population III stars (in the absence of dark matter heating) are expected to have masses in the range $10-100 M_\odot$ - too faint to be seen as individual objects with JWST (Oh 1999; Oh et al. 2001; Gardner et al. 2006; Rydberg et al. 2010). However a galaxy containing $10^5 - 10^7 M_\odot$ of Pop III stars might indeed be detectable. Zackrisson et al. (2011a) presented a comprehensive study of the integrated spectra signatures of Pop III stars in the wide filters of JWST. Their main findings are that Pop III galaxies could be detectable to redshifts as high as 20 if the stellar population mass is $\sim 10^7 M_\odot$ (or in the case of $10^5 M_\odot$ stellar population mass up to redshifts of 10). A

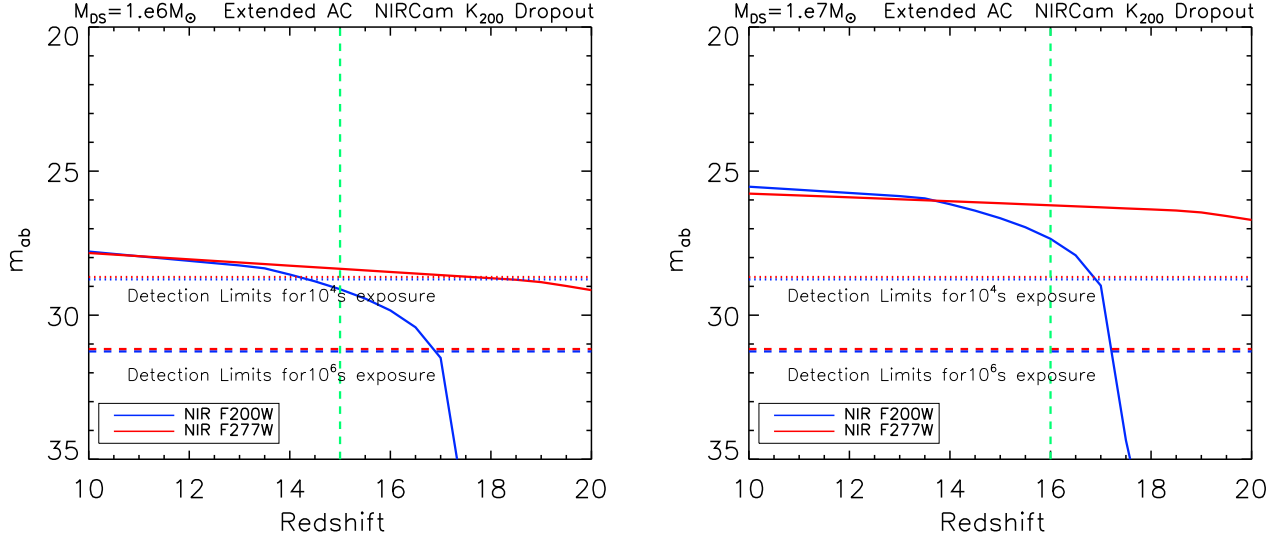


Figure 14. SMDS with JWST as K_{200} band dropouts: Apparent magnitudes for SMDS formed without DM capture through the F200W and F227W Nircam filters. Left panel: for the $10^6 M_{\odot}$ dark star. Right panel: for the $10^7 M_{\odot}$ dark star. The vertical green dashed line indicates the minimum redshift at which the DS will appear as a dropout.

similar study by Pawlik et al. (2011), who examined nebular emission lines from early galaxies, came to the same conclusion: thousands of these may be found with JWST. Moreover, Inoue et al. (2011) and Zackrisson et al. (2011a) have proposed selection criteria using two of the filters of JWST: Inoue et al. (2011) argued for using two NIRCAM filters and Zackrisson et al. (2011a) argued for adding imaging in two MIRI filters to more cleanly differentiate between Pop III galaxies and Pop II or Pop I galaxies at $z \sim 7 - 8$. Indeed these authors found that galaxies containing Pop III stars at high redshift are typically brighter in most JWST filters than later generations of stars; thus galaxies with Pop III stars would be the most likely source of confusion in identifying dark stars.

Using the Yggdrasil⁴ model grids (Zackrisson et al. 2011a, see <http://ttt.astro.su.se/~ez/>) we compare signatures in the NIRCcam passbands of Pop III galaxies at $z \sim 10 - 15$ with those of SMDS. All the nomenclature used here for Pop III galaxies follows Zackrisson et al. (2011a): we consider three different Initial Mass Functions (IMF) for Pop III galaxies:

- Pop III.1: A zero-metallicity population with an extremely top heavy IMF and a Single Stellar Population (SSP) from Schaerer (2002) with a power-law IMF ($dN/dM \propto M^{-\alpha}$). The population has stellar masses in the range $50 - 500 M_{\odot}$ and a Salpeter slope $\alpha = 2.35$ for the entire mass range.

- Pop III.2: A zero-metallicity population with a moderately top-heavy IMF. A SSP from Raiter et al. (2010) is used. This model has a log-normal IMF with characteristic mass $M_c = 10 M_{\odot}$ and dispersion $\sigma = 1 M_{\odot}$. The wings of the mass function extend from 1 to $500 M_{\odot}$.

- Pop III, Kroupa IMF: In view of recent simulations (e.g. Greif et al. 2010) the mass of Pop III stars might be lower

than previously predicted. Therefore in this case a normal Kroupa (2001) IMF, usually describing Pop II/I galaxies, is used. The stellar masses range in the $0.1 - 100 M_{\odot}$ and the SSP is a rescaled version of the one used in Schaerer (2002)

Following Zackrisson et al. (2011a) we further subdivide the models into two types, based on the amount of nebular emission. The first galaxies are expected to have significant ionized gas surrounding them. Depending on how compact the HII region is, the escape fraction for ionizing radiation from the galaxy into the IGM can vary anywhere from 0-1. Hence we consider the two extreme possibilities:

- Type A galaxies: If the gas covering fraction $f_{cov} = 1$, then there is maximal nebular contribution to the SED and no escape of Lyman continuum photons.
- Type C galaxies: If $f_{cov} = 0$, there is no nebular contribution to the SEDs and instead stellar light dominates the SED. We will not consider here the intermediate case of Type B galaxies.

Zackrisson et al. (2011a) argue that the nebular emission typically dominates the spectrum of young Pop III galaxies at $z \sim 10 - 15$; e.g. at $z=10$ nebular emission dominates for galaxies younger than 10 Myr. All young or star forming galaxies are expected to have significant contribution to the SEDs from nebular emission, and this effect is increased with lower metallicity or a more pronounced top heavy IMF. Hence we will predominantly focus on Case A of maximal nebular emission from the early galaxies.

In Figure 15 we plot the SEDs (in apparent magnitudes) of SMDS and Pop III galaxies at $z=12$ as a function of wavelength. Our interest is in their detectability with the NIRCcam and MIRI cameras on JWST. The vertical dotted line demarcates the wavelength ranges covered by the two instruments, and the dark blue horizontal segments represent band widths and the sensitivity limits of individual filters

⁴ We highly recommend watching the movie Thor to understand this name.

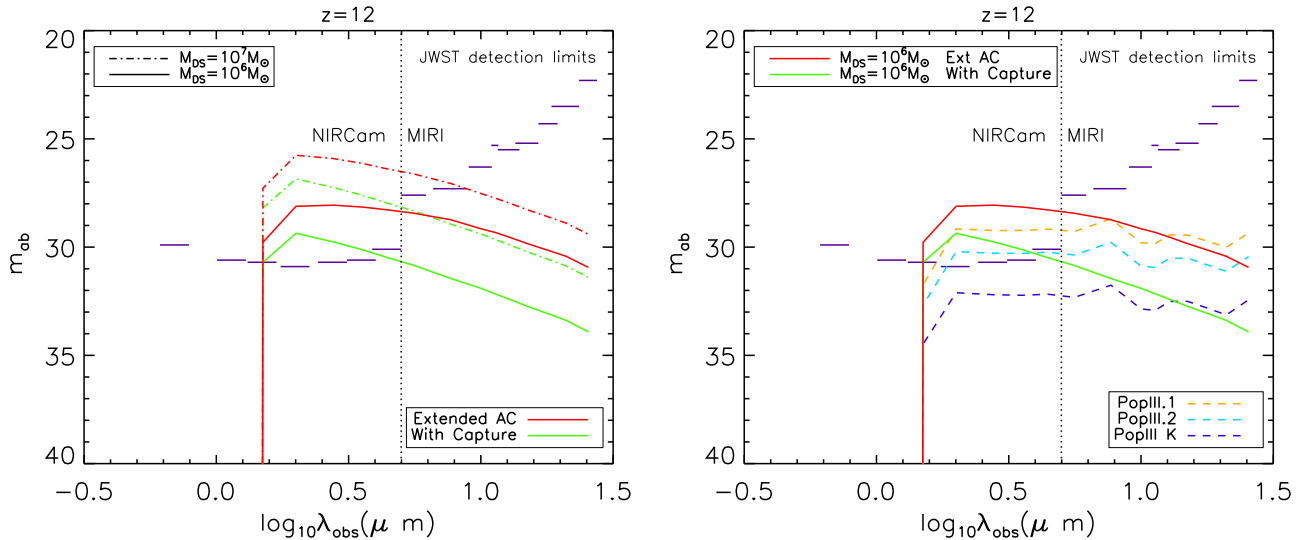


Figure 15. JWST detection limits and apparent magnitudes of SMDS and Pop III galaxies. Each filter’s sensitivity limit for JWST NIRCam and MIRI wide filters for 100 hours of exposure time is plotted as a segment at the corresponding wavelength. Left panel: Apparent magnitudes for SMDS in the $10^6 M_{\odot}$ (solid lines)- $10^7 M_{\odot}$ (dash-dotted lines) mass range for both extended AC (red lines) and Capture (green lines) formation mechanisms. Right panel: Apparent magnitudes of SMDS of $10^6 M_{\odot}$ (solid lines) and Pop III instantaneous burst galaxies of 1 Myr age (dashed lines) with the same stellar population mass as the SMDS.

assuming a 100 hour exposure⁵. In the left panel we plot the apparent magnitudes for 10^6 and $10^7 M_{\odot}$ DS formed via both Extended AC and Capture mechanisms. We have previously discussed (see Figures 10 and 11) that both 10^6 and $10^7 M_{\odot}$ DS are bright enough to be observed by the NIRCam filters. On the other hand, in the less sensitive MIRI filters, $10^7 M_{\odot}$ DS can be seen in the lowest two wavelength filters (F560W and F770W) but $10^6 M_{\odot}$ DS are too faint to be observed.

In the right panel we compare the observed SEDs of $10^6 M_{\odot}$ SMDS (solid curves) with Pop III galaxies (dashed curves). For the galaxies we assumed an instantaneous starburst (at $t = 0$) and used the results from the Yddgrasil code at 1 Myr after the burst. The light from the galaxies is assumed to be dominated by nebular emission (Type A) (Zackrisson et al. 2011a) for galaxies younger than 10 Myr. We have taken the stellar mass of the galaxy to be the same value $10^6 M_{\odot}$ as the DS mass. SMDS are brighter than the galaxies in all filters in which the objects are potentially visible. The sharp cut off in flux at $\log_{10} \lambda_{obs} \sim 0.02$ is due to Ly- α absorption. For a stellar population mass of $10^6 M_{\odot}$, Pop III.1 galaxies are detectable as a H_{150} dropouts in a deep field survey with an exposure of 100 hours; Pop III.2 are still just above the sensitivity limits; but Pop III galaxies with a Kroupa IMF are not detectable as H_{150} dropouts.

Let us imagine that an object has been detected as a photometric dropout at some redshift, say an H-band dropout at $z = 12$. Our goal is to determine the nature of this object, i.e., to differentiate SMDS from first galaxies with JWST. One approach would be to exploit the emission lines in galaxies that are not shared by the DS. Pawlik et al. (2011) have shown that there would be several major sig-

natures in the spectra for Pop III galaxies with significant nebular emission (our Case A), including the HeII line at $0.1640 \mu\text{m}$ and H α emission. They found that JWST spectrometers (NIRSpec and MIRI) are indeed sensitive enough to detect these emission lines, thereby potentially finding up to tens of thousands of star-bursting galaxies with redshifts $z \geq 10$ in its field of view of $\sim 10 \text{ arcmin}^2$. They also found that the He1640 recombination line is only detectable in significant numbers for the case of zero-metallicity starbursts with top-heavy IMF. They noted that their estimates are consistent with previous estimates of JWST starburst counts (e.g. Haiman & Loeb 1998; Oh 1999). A third possibility would be to detect the continuum limit of the Balmer series at $0.3646 \mu\text{m}$ in the rest frame.

In short, if followup spectroscopy is done on an object found as a dropout with JWST, the detection of a HeII 1640 emission line or an H α emission line would most likely indicate that the object is a Pop III galaxy with nebular emission rather than a SMDS (later stellar populations e.g. Pop II would also be missing these emission lines, but would not be as bright as either Pop III galaxies or SMDSs). We do, however, note one caveat: if there is any supernova (SN) explosion that can result from the end of SMDS evolution, there might be another way to make He II 1640 radiation. When the SN remnant shock reaches the radiatively cooling stage of its evolution (i.e. when postshock gas cools radiatively faster than it does by adiabatic expansion), the shock becomes a “radiative shock”, and that usually means that gas cools from a postshock temperature above a million degrees, down to 10^4 K or below, and He II line emission will also occur. The shocks that do this need not only be SN explosion shocks, but could also be halo virialization shocks, for halos large enough to have virial T high enough to ionize He II to He III. On the other hand, as discussed above, Heger (personal communication Oct 2011) finds that (in the absence of rotation), fusion powered stars more mas-

⁵ For NIRCam we did not plot the F090W filter, since the throughput profile is not yet available.

sive than $153,000 M_{\odot}$ collapse directly to supermassive black hole seeds rather than blowing up as SN.

While the detection of emission lines most likely indicates that the object is a Pop III galaxy rather than a SMDS, the lack of emission lines leaves both possibilities still open. One might therefore ask how well the underlying continuum spectrum can be determined with JWST. The UV continuum slopes for galaxies in the redshift range $2 - 8$ have been analyzed using HST data in the literature (e.g. Bouwens et al. 2009, 2010; Dunlop et al. 2011; Finkelstein et al. 2011; McLure et al. 2011). The value of β can be determined by converting photometric colors in relevant filters (as in Bouwens et al. (2010) or Dunlop et al. (2011) for HST), but as noted in McLure et al. (2011) the photometric errors can be quite large, of $\mathcal{O}(1)$. Based on our initial estimates it will be difficult to disentangle the SMDS from PopIII galaxies based on UV continuum slopes calculated from AB magnitude colors in NIRCcam or via spectroscopy with NIRSpec. A detailed study of how well this separation can be done based on UV spectra is the subject of future work.

The HeII line in Pop III type A galaxies due to nebular emission at $0.1640 \mu\text{m}$ would fall within the F200W filter of JWST for sources at redshifts $9.7 < z < 12.7$. The strength of the line is modeled in the Yggdrasil code for all PopIII galaxies we have considered. Since this line is pronounced in Pop III galaxies but not in DS, one could examine the difference in the two magnitudes $m_{150} - m_{200}$, which would be significantly more negative (i.e. bluer $m_{150} - m_{200}$ colors) for DS than for the galaxies. One should be able to see this effect for objects at $z < 12$. At higher redshifts, however, the Gunn-Peterson cuts off significantly the fluxes in the F150W filter, so that it would be impossible to distinguish an increase of F200W flux (due to HeII in Pop III galaxies) from a decrease of F150W flux (due to Ly- α absorption).

Another approach to distinguish between different types of objects is their location in color/color plots. Previously Inoue et al. (2011) and Zackrisson et al. (2011a) used color/color plots to distinguish between different types of galaxies: ones with Pop III.1 stars vs. ones containing a later population of stars. In Figure 16 we try out the possibility of differentiating DS vs. galaxies, based on their locations in color/color plots. In the left and right panels we study Pop III instantaneous burst galaxies of Type A (maximal nebular emission) and Type C (no nebular emission) respectively. We focus here on objects at $z=12$ as this is the most favorable redshift to look for SMDSs. The empty circle (cross) symbols correspond to magnitudes for SMDS of $10^6 M_{\odot}$ ($10^7 M_{\odot}$). The solid lines represent the evolutionary tracks of Pop III galaxies obtained using the Yggdrasil model grids, with points marking three different ages (diamonds for 1 Myr, triangles for 3 Myr, and squares for 10 Myr). We note that, due to the similar temperatures, SMDS formed “with capture” of either $10^6 M_{\odot}$ or $10^7 M_{\odot}$ occupy the same spot on the diagrams.

Pop IIIA galaxies with lifetimes less than 10 Myr will exhibit redder colors than SMDS in the $m_{356} - m_{444}$ (see lower left panel) due to the increased fluxes in the F444W filter due to the Balmer emission lines from the galaxies. One might therefore hope to distinguish between SMDS and Pop III type A galaxies at $z \sim 12$ would be to look for red colors in $m_{356} - m_{444}$. Indeed for the case in Figure 16, this

technique would work: only the Pop III.1 galaxies are bright enough to compete with SMDS (see Figure 15), yet these are in a distinctly different location on the color/color plot from the SMDS. However, in the figure we have taken the stellar mass of the galaxies to be $10^6 M_{\odot}$, while this number could be an order of magnitude higher, which would drive the Pop III lines in the Figure closer to the SMDSs. As pointed out before, the error bars in the magnitudes for 10σ detections are ~ 0.15 , comparable to the differences in magnitudes between galaxies and SMDS. In addition, in the figure we have taken a specific star formation rate (instantaneous burst). For comparison we have also tried a constant SFR and found that the results do not change much (the colors become slightly bluer). Differentiating between SMDS and Pop III galaxies (of uncertain stellar mass and metallicity) with such color-color plots will be difficult.

Differentiating between SMDS and galaxies containing Pop III galaxies is an important issue. Using JWST, the best bet is to look for emission lines of He 1640 or H α . If these are found the object is not likely to be a SMDS. On the other hand, if these are not found, then differentiating between SMDS and Pop III.1 galaxies may be difficult with JWST. Further studies with other instruments, specifically ground based spectrometers, may prove to be helpful.

7 SUMMARY AND CONCLUSIONS

The first phase of stellar evolution may have been dark stars, powered by dark matter annihilation. These form inside early $10^6 - 10^8 M_{\odot}$ halos at $z=10-50$. Initially DS are puffy objects with masses of $1 - 10 M_{\odot}$ and radii ~ 10 A.U. As long as they are DM powered, their surface temperatures ($\sim 10^4$ K) remain cool enough to allow continued growth via accretion of baryons until they become supermassive $M_{SMDS} \sim 10^6, 10^7 M_{\odot}$. The requisite DM fuel can be acquired in two ways: (i) extended adiabatic contraction due to DM particles on chaotic or box orbits in triaxial haloes and (ii) capture of DM particles via elastic scattering off nuclei in the star. In this paper we have studied the detectability of Supermassive Dark Stars formed via both mechanisms with upcoming JWST observations.

In order to determine their observational characteristics, we obtained the spectra of SMDSs with the TLUSTY stellar atmospheres code (Figure 1). We used N-Body simulations for structure formation at high redshifts (Iliev et al. 2010) to obtain estimates for the numbers of DM halos capable of hosting SMDS (Figure 2 and Table 1). Then we used HST observations to set limits on their detectability.

Both 10^6 and $10^7 M_{\odot}$ SMDS could be seen in HST data and would be detected as J-band dropouts. Since Bouwens et al. (2011) report only one plausible $z \sim 10$ object in the data, we used the fact that at most one observable DS at this redshift can exist to obtain bounds on the possible numbers of DS in Eqns. 11 and 12.

SMDSs are bright enough to be seen in all the wavelength bands of the NIRCcam on JWST, while detection is more difficult in the less sensitive higher wavelength MIRI camera. We showed that SMDSs could be seen as J-band, H-band, or K-band dropouts, which would identify them as $z \sim 10, 12$, and 14 objects respectively.

The strong point of JWST will be its sensitivity to

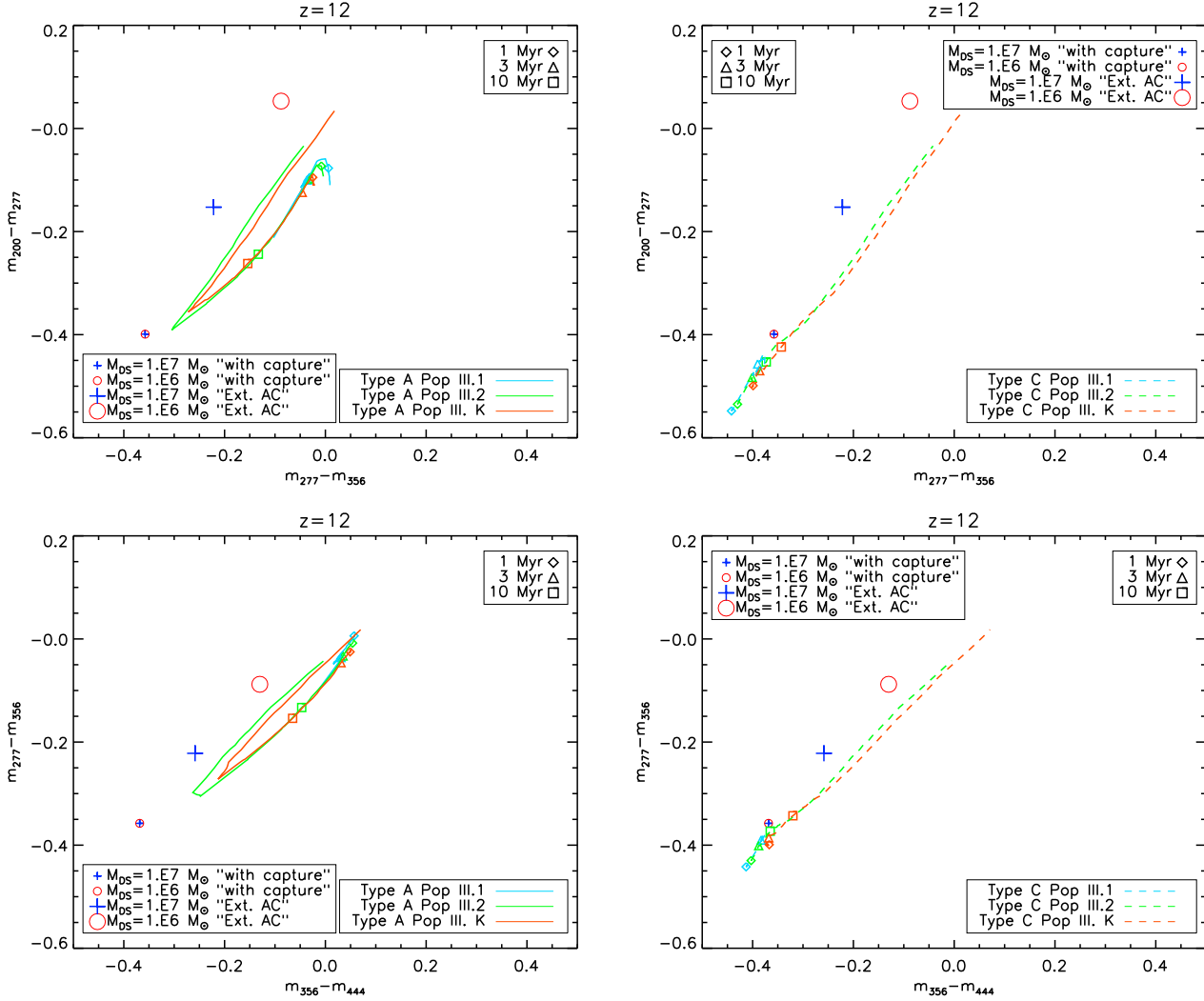


Figure 16. Signatures of SMDS and instantaneous burst Pop III galaxies in $m_{277} - m_{356}$ vs $m_{200} - m_{277}$ (top row) and $m_{356} - m_{444}$ vs $m_{277} - m_{356}$ (bottom row) color diagrams. The left column corresponds to Type A Pop III galaxies (maximal nebular emission) and the right column to Type C Pop III galaxies (no nebular emission). The solid lines are evolutionary tracks for Pop III galaxies obtained using the Yggdrasil model grids introduced in Zackrisson et al. (2011a). The points along the evolutionary tracks single out the evolution at three different ages of the galaxies. $10^6 M_{\odot}$ ($10^7 M_{\odot}$) SMDS are represented by circle (cross) symbols in the diagrams. For the extended AC case we chose a larger size symbol compared to the SMDS formed “with capture”.

longer wavelengths than HST, corresponding to light from higher redshifts where SMDSs may be found. While JWST is not particularly better than HST at finding J-band dropouts, it will be significantly better at finding SMDS as H-band and K-band dropouts.

We can summarize our predictions for the numbers of SMDS seen as H-band dropouts with JWST as:

$$N_{obs} = 4.4 \times 10^5 f_{smds} f_{\Delta t} (\theta/150 \text{ arcmin})^2 \quad (M_{DS} = 10^6 M_{\odot}) \quad (13)$$

$$N_{obs} = 2.4 \times 10^3 f_{smds} f_{\Delta t} (\theta/150 \text{ arcmin})^2 \quad (M_{DS} = 10^7 M_{\odot}) \quad (14)$$

where we have scaled the results to 150 arcmin^2 survey area, which would require multiple surveys by JWST.

Similarly, our predictions for the numbers of SMDS seen

as K-band dropouts are:

$$N_{obs} = 7 \times 10^4 f_{smds} f_{\Delta t} (\theta/150 \text{ arcmin})^2 \quad (M_{DS} = 10^6 M_{\odot}, \text{AC}) \quad (15)$$

$$N_{obs} = 120 f_{smds} f_{\Delta t} (\theta/150 \text{ arcmin})^2 \quad (M_{DS} = 10^7 M_{\odot}). \quad (16)$$

$10^6 M_{\odot}$ SMDS formed via Capture are not detectable.

Although these numbers are quite large, as we have emphasized throughout it is quite likely that $f_{smds} f_{\Delta t} \ll 1$. If the DS survives to $z \sim 10$, HST observations bound this product. Our final predictions for numbers of SMDS that could be detected by JWST are found in Tables 3 and 4.

Differentiating between SMDS and galaxies containing Pop III galaxies is an important issue. Using JWST, the best bet is to look for emission lines of He 1640 or H α . If these are found the object is not likely to be a SMDS. On the other hand, if these are not found, then JWST will have

trouble differentiating between SMDS and early galaxies. Thus further estimates are required using instruments such as Giant Magellan Telescope, TMT, LSST, and others.

As argued by Heger (Heger, private communication) in the absence of a dark star phase, the characteristic mass for big BHs at birth is $153,000 M_{\odot}$ (i.e., once a fusion powered star accretes this much mass it can no longer sustain hydrostatic equilibrium and collapses directly to a BH. With a dark star phase, the DS could instead grow to a larger mass while DM powered, and then collapse directly to a BH; thus in this case the BH could be born with larger masses. Future observations of large BHs might thus be able to differentiate someday between formation mechanisms via dark stars or fusion powered stars.

SMDS mass as a function of halo mass: Although we have assumed in this paper that DS grow to the point where they consume most of the baryons in the haloes that host them, one can examine how the results would change if we were to stop the growth at a smaller fraction of the total baryonic content. For the case of "maximal bounds" we can show that the resulting predictions for JWST remain identical. For example, the case we considered in the paper of $10^6 M_{\odot}$ SMDS that grew inside $\sim 10^7 M_{\odot}$ haloes, can be compared instead to the case of $10^6 M_{\odot}$ SMDS that grew inside $\sim 10^8 M_{\odot}$ haloes. For the case of "maximal bounds", which assumes that HST bounds at $z=10$ apply directly to SMDS at $z=12$ (i.e. that the SMDS at $z=12$ survive all the way to $z=10$), we find that our results are completely unchanged. The number of $10^8 M_{\odot}$ haloes is smaller than the number of $10^7 M_{\odot}$ haloes at both redshifts $z=10$ (so the HST bounds are weaker) and at $z=12$ (where the JWST observations are made). Thus the two effects cancel exactly. One can see this cancellation in the following way. The numbers of SMDS observable in either HST or JWST are given by the same equation, Eq.(9). The two factors $\frac{dN}{dzd\theta^2}$ and $f_{SMDS}(z = z_{start})$ change depending on the hosting halo mass, but their product remains the same since it is set by HST bounds in Eq.(10). Thus the numbers with JWST are unchanged regardless of halo size.

The current decade is a time of great excitement in the physics community regarding the possibility of detection of the dark matter particle. Three approaches are being pursued in the hunt for Weakly Interacting Massive Particles: direct detection (including DAMA, CDMS, XENON, COGENT, CRESST, ZEPLIN, TEXONO, COUPP, and many others worldwide), indirect detection (including PAMELA, FERMI, ICECUBE), and colliders (LHC). Many of these experiments have indeed found hints of a signal, though confirmation in more than one type of detector of the same particle remains a goal. Dark Stars offer a fourth possibility for the discovery of WIMPs, or of learning about their properties. If WIMPs are indeed discovered, then it is very reasonable to expect to find Dark Stars in the sky that are WIMP powered. It is even possible that the WIMPs have the property that they will be seen first by JWST before any other experiment. In either case the prospect of finding a new type of star in the next premier NASA mission is greatly exciting.

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